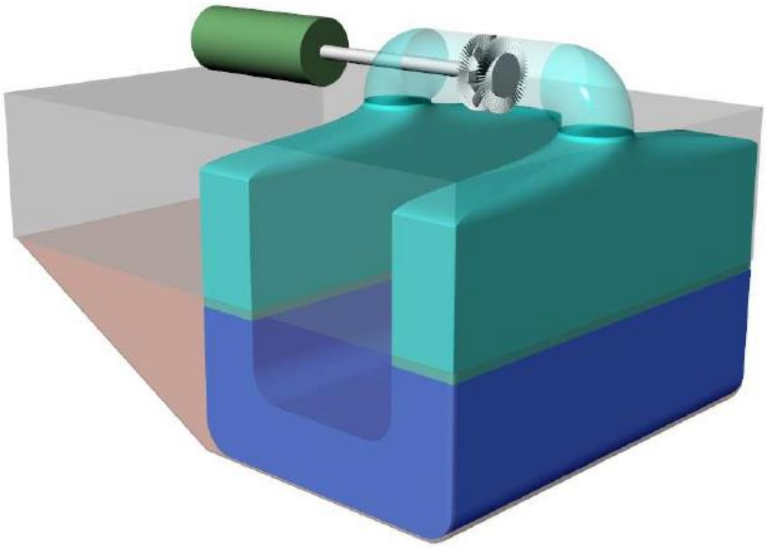

Cost analysis of the UGEN

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Thesis to obtain the Master of Science Degree in

Mechanical Engineering

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September of 2016

Acknowledgments

Firstly, I would like to express my gratitude to Prof. António Sarmento for giving me the opportunity to develop my Master thesis at the company WavEC Offshore Renewables.

I am especially thankful to Boris Teillant for his supervision, his constructive feedback and his helpful role as a tutor giving me advices and directing me even with the added difficulty of the communication situation.

I would like to thank Sergio Ribeiro for his support and continuous emerging ideas that have improved the outcome of the thesis.

Finally, I would like to thank Marta Silva for her continuous assistance and help.

Abstract

Key words: UGEN, WEC (Wave Energy Converter), OWC (Oscillating Water Column), LCOE (Levelised Cost of Energy), CAPEX (Capital Expenditures) and OPEX (Operational Expenditures).

The world energy consumption is estimated to increase considerably over the next decades. In the dynamic evolution of the renewable energy sector, a wave energy industry is emerging. Although wave energy technologies are still relatively immature, interest from the governments and industry is steadily increasing.

The UGEN device is a wave energy converter developed by Instituto Superior Técnico with the support of the R&D-based company WavEC Offshore Renewables. A scaled prototype that has been tested in the laboratory and the numerical simulations performed with standard wave-to-wire models have proven the capability of the device to generate electricity and its potential to become economically viable. The aim of this master thesis is to carry out a techno-economic analysis study of the UGEN in order to further assess the economic viability of this technology.

The Master thesis has concluded that the levelised cost of electricity (LCOE) of the UGEN has been found to be 59.01 c€/kWh =590.1 €/MWh. Compared to other renewable sources the UGEN still requires of further developments and optimizations in order to achieve the competitiveness of the market. The opportunities for cost reductions that have been analysed may lead to a significant cost decrease although further studies will be required to evaluate the final cost reduction.

Index

Acronyms and abbreviations

WEC	Wave Energy Converter
IST	Instituto Superior Técnico
PTO	Power Take-Off
LCOE	Levelised Cost Of Electricity
TRL	Technology Readiness Level
CG	Gravity Center
DoFS	Degrees-of-freedom
COBYLA	Constrained Optimization BY Linear Approximation
GA	Generic Algorithm
AEP	Annual Energy Production
CP	Capacity Factor
CAPEX	Capital Expenditures
M&E	Mechanical and electrical plant
OPEX	Operational Expenditures
OEM	Original Equipment Manufacturer
OWC	Oscillating Water Column
O&M	Operation and Maintenance
DCF	Discount Cash Flow

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1. Introduction:

1.1. Motivation and framework

1.1.1. Why the thesis

Today's energy supply is mostly based on fossil fuels such as oil and gas. During the last century, those resources have made industrialization possible, but at a high cost with large CO2 emissions. In addition, these fossil resources are shrinking while the global demand for energy increases. Therefore, it is essential to find alternative energy sources. Renewable energy sources are a solution in the global search for long-term sustainable development to cope with the energy demand of the world. The ocean waves are an important renewable energy resource that, if extensively exploited, may contribute significantly to the electrical supply of countries with coasts facing the sea.

Until now, a wide variety of designs of wave energy converters (WEC) have been studied, presented or tested. However, wave energy generation technology requires further development in order to converge to the optimal power generation and reach a commercial stage.

In the past, the tendency of the WEC developers was to test the device as soon as possible with increasing scales as quickly as possible. A scaled model or a full-scale WEC is providing a better understanding of the working principles of the device but it often requires significant investment to build the prototypes and run the tests. Moreover, feedback from experimental data leading to a modification in the design is likely to require a repetition of the tests. Nowadays, thanks to major development progress in software simulation and analysis tools, it is generally recommended to extensively and iteratively carry out in-depth numerical and engineering destock studies before constructing prototypes or full-scale pilot machines.

The UGEN is a floating WEC. A novel concept developed by IST (Instituto Superior Técnico) based on three main reliable and mature concepts that have been extensively studied over the past 30 years. Firstly, the hull shape has been inspired on the Salter's Duck device. One of the most well-known WEC. Appearing in 1974, in Edinburgh the Salter's duck remains today the object of several R&D work and has inspired numerous WEC technology developers. Secondly, inside the hull the Power Take-Off (PTO) mechanism is embodied within a U-tank sealed reservoir partially filled with water. The U-tank is encapsulated in the same manner as ballast U-tanks used in vessels for ship stabilization purposes. Vessel operators can adjust the water inside the U-tank in order to minimize the roll motion and reduce risks and damages while sailing. However, the aim of the U-tank of the UGEN is somehow the opposite as it is intended to maximize the roll motion of the WEC with the objective to increase the electrical power production. Finally, the mechanical to electrical energy conversion is accomplished by a Wells turbine. This turbine first appeared on the market in 1976 and has been installed in few full scale WEC over the past 30 years. Alternative, more advanced air turbines for WEC can alternatively be used in the UGEN.

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In 2010 an experimental program with a 1:16 scaled model of the UGEN was carried out at IFREMER, France. Data from the experimental campaign and complementary numerical simulations have shown the capability of the concept to generate electrical power.

Once the capability of the device to generate electrical power was confirmed, a simplified Levelised Cost Of Electricity (LCOE) analysis was carried out to determine the techno-economic potential of the UGEN concept. The initial calculations of the LCOE for the UGEN was found to be 25.6 c€/kWh. However, the analysis was performed with a low level of details. A more sophisticated LCOE model is therefore required.

The Technology Readiness Level (TRL) is based on a scale from 1 to 9, with 9 being the most mature technology, ready to be commercialised [1]. To-date, the UGEN is considered between the level 3 (experimental proof of concept) and level 4 (technology validated in laboratory). The objective of the UGEN development team is to achieve level 9 which is equivalent to a commercial stage of development. The steps to reach commercial maturity are the technology development, technology demonstration, system & subsystem development and system test, launch & operations. The development path of a WEC is strongly linked to the capacity of reducing its LCOE. As a result, it is recommended to set up a continuous feedback system from the projected LCOE in order to identify the major costs of the device and possible reductions or alternatives before and while the technology, the systems and the subsystems are being developed. The present Master thesis precisely aims at providing a detailed analysis of the LCOE of the UGEN WEC.

1.1.2. State of the art

Wave energy converters

The waves are produced by the action of the wind over the surface of sea/oceans and are therefore an indirect form of solar energy (because wind originates from the difference of temperature in the atmosphere caused by the Sun). The primary purpose of a WEC is to harness the energy content in ocean/sea waves to generate electricity.

Pioneering work in WECs began in 1940s in Japan with Yoshio Masuda. He developed a navigation buoy powered by wave energy, equipped with an air turbine. Since then a wide variety of WEC technologies has been proposed, studied, and in some cases tested at full size in real ocean conditions.

Wave energy resource.

As long as the waves propagate slower than the wind speed just above the waves, there is an energy transfer from the wind to the waves. For deep waters the power that is transported by a wave follows equation (1.1) below:

$$P = \frac{\rho g^2}{64\pi} H_{mzo}^2 T_e \qquad (1.1)$$

- P [W/m]: Wave energy flux per unit of wave-crest length.
- ρ [kg/m³]: Density of the fluid, for the sea 1.025 kg/m³.
- g [m/ s²]: Gravity, 9.81 m/ s².
- H_{mzo} [m]: Significant wave height
- T_e [s]: Wave energy period.

It can be seen that the power of the wave only depends on the significant wave height and the period of the waves. The wave energy level is expressed as power per unit length (usually in kW per meter along the wave crest, which tend to become parallel to the shoreline in shallow waters). The typical values for ‘‘good’’ offshore locations (annual average) ranges from 20 to 70 kW/m. Reviews on wave energy resource characterization can be found in [2, 3].

Hydrodynamic modelling of WEC

The ability of a WEC to convert mechanical energy from the waves to the WEC machine itself generally resides in the hydrodynamic characteristics of the WEC. This section will introduce the main hydrodynamic governing equations of floating WEC systems. The motions of a floating body in contact with a fluid can be seen in Figure 1.1:

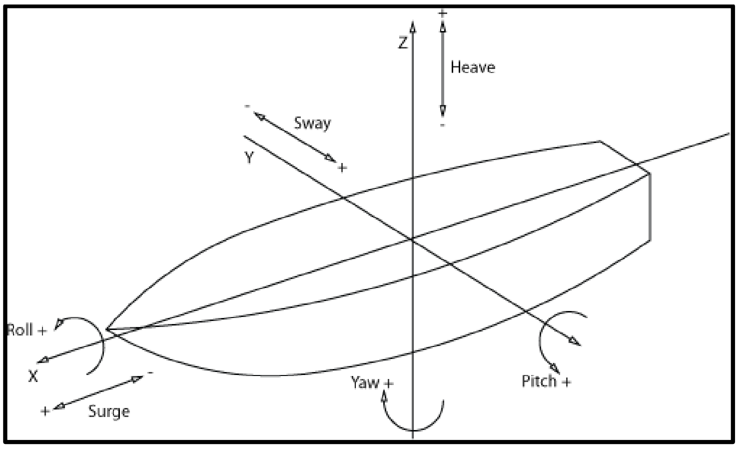


Figure 1.1. Movements of a body in contact with a fluid [4]

The forces on the wetted surface of a body can be decomposed into, [5]:

- Diffraction Forces: relates to the forces induced by the incident wave field assuming the floating body remains fixed (i.e without motion).
- Radiation Forces: relates to the forces induced by the body in motion under an undisturbed fluid.
- Hydrostatic forces: are the normal forces exerted on a submerged object due to the hydrostatic pressure. The hydrostatic pressure is the equilibrium pressure at a point exerted by a fluid. The hydrostatic pressure depends on the depth of the given point and the density of the fluid.

For a simple case of a floating WEC single-body oscillating in heave only (single degree of freedom corresponding to the vertical translation) [5], the equation of motion is given by the following equation.

$$(m + A) \cdot \ddot{x} = f_d - B\dot{x} - \rho g x S + f_{PTO} \quad (1.2)$$

- *m* [kg]: Dry mass of the body.
- *x* [m]: Vertical coordinate.
- f_d [N]: Vertical component of the diffraction force.
- f_{PTO} [N]: Vertical component of the force due to the PTO mechanism.
- *A(ω)* [m]: Hydrodynamic coefficient of added mass due to water surrounding inertia.

- $B(\omega)$ [kg/s²]: Radiation damping coefficient associated with the average energy transferred between the body and the waves that it generates.
- ω [rad/s]: Angular frequency.
- $\rho g x S$: Hydrostatic restoring force.
  - ρ [kg/m³]: Density of the fluid, for the sea 1.025 kg/m³.
  - g [m/ s²]: Gravity, 9.81 m/ s².
  - S [m²]: Water plane of the WEC.

If we consider that the Power Take-Off (PTO) can be represented as a linear damping system, such as in equation (1.3).

$$f_{PTO} = -C\dot{x} - kx \tag{1.3}$$

- C [kg/s]: Linear damping coefficient.
- k [kg/s²]: Linear spring coefficient.

Considering equations (1.2) and (1.3) with k = 0, it can be shown that for a given frequency of the waves there is an optimal linear damping system, that would optimize the power extracted [5]. This optimal point occurs when the PTO damping coefficient matches the radiation damping. But this optimal value, results to be efficient for a narrow band of wave periods as the radiation damping changes significantly with frequency, see equation (1.4).

$$C_{opt} = B(w) \tag{1.4}$$

Also, real waves are not monochromatic and so a range of frequencies are simultaneously present, which to some extend reduces the interesting result from equation (1.4).

Results for a single-mode oscillator can be extrapolated to oscillating-body converters with more than one degree of freedom.

WEC technology types

The wave energy absorption is a hydrodynamic process by which one can harness energy. The PTO mechanism is the system that allows the conversion of the wave mechanical power into electrical power. Various PTOs mechanisms were conceived over the years as well as different WEC concepts. In Table 1.1, the different types of PTOs are presented. For a more detailed explanation and examples see Annex A.

	Explanation
Oscillating water column	Most devices are opened below the water surface where air is trapped inside a chamber open to the atmosphere through an orifice that contains an air turbine. This air is compressed and decompressed due to the motion of the waves changing the water level inside the chamber. This engenders high and low pressure cycles driving air through the air turbine to and from the atmosphere.
Oscillating bodies	The bodies can be floating or fully submerged. The WEC system relies on (at least) two main parts and the relative movement between them. Example with heave translation mode: One part/body is heaving faster than the other one due to their inherent hydrodynamic and mass properties. The relative movement between both parts can actuate various PTO mechanisms, e.g a linear electrical generator, a pinion and rack system or a hydraulic system. Rotation mode: These devices take advantage of the of the wave propagation by inducing a rotation or articulation that may be used to pump high pressure oil, slide a mass, pump a hydraulic system...
Overtopping	The device captures the water that is close to the wave crest and introduce it, by over spilling, into a reservoir where it is stored at a level higher than the average free-

	surface level of the surrounding sea. The potential stored energy is converted through low-head hydraulic turbines.

Table 1.1. The types of PTO and the definition of each one.

Oscillating water column

The content of this section is based on an article written by António F.O. Falcão [5]. For the definition of the OWC see Table 1.1.

The OWC is a wave energy device-type that consists of a fixed or floating hollow structure, open to the sea below the water surface, which traps air above the inner free-surface. Wave action alternately compresses and decompresses the trapped air which is forced to run through a duct connecting to the atmosphere where an air turbine is coupled to a generator.

Unless rectifying valves are used, a self-rectifying turbine is needed to maintain the direction of the turbine unchanged regardless the air flow. The more popular self-rectifying turbines are axial-flow Wells turbine and self-rectifying impulse turbines.

In Annex B the different designs of OWCs proposed so far are shown.

Before 1990 the OWC prototypes were predominantly fixed, such as the plant of Toftestallen in Norway, see Annex B. Although in the late 1980s, the first floating OWC devices offshore appeared in Japan, called Backward Bent Duct Buoy. Alternative onshore-based fixed OWC solutions consisting of integrating the WEC system into a breakwater have also been investigated and tested, such as the plant in Spain called Mutriku. Using this type of plant, the construction costs are shared, and the access for construction, operation and maintenance become easier. In 1999 a 400 kW OWC was built in the island of Pico and is still running in 2016. This plant in now owned and operated by WavEC.

It can be said that an efficient wave energy absorber should be an efficient wave radiator. In fixed-structure WEC systems, the wave radiation is induced only by the water column motion. In floating devices, the contribution from the structure motions and the water column oscillations are comparable, which may be regarded as a positive feature if properly controlled.

The relevance of the OWC to the present thesis is the similitude between the U-tube operation and the OWC internal water flow.

1.2. Objectives

The objectives of the Master thesis are:

- Obtain a more accurate value of the LCOE: the aim of the project is to determine a new value of the LCOE for the UGEN concept under a well-defined scenario by developing a more sophisticated LCOE model.
- Identify the main drivers of the LCOE: perform sensitivity analysis of key uncertain parameters to understand their impact on the LCOE

- Quantify the potential cost reductions: evaluate alternatives solutions than the ones of the reference case in order to quantify the potential cost decrease of the WEC power plants. Consider the future cost reductions that could be achieved through learning rates and bulk factors.

1.3. Presentation of the thesis

The thesis is composed of five main parts. The second chapter introduces the UGEN by presenting the components that have inspired this WEC. Next, patents and previous work undertaken before the present Master thesis are summarized. In particular, the mathematical model that has been used to design the first generation of the UGEN concept and its validation with experimental data are reported.

The third part provides an explanation of the LCOE metric and its major components detailing how these are obtained or calculated. Subsequently, WavEC's techno-economic model is introduced. The input values of the WavEC's model assumed for the reference case are also given.

In the fourth part, the case study is depicted. The location of the wave farm and the farm design are first disclosed together with other general characteristics of the reference case study. Then, the LCOE value and desegregation are displayed and compared with the literature.

The fifth and last part of the thesis focuses on the identification of the drivers of the LCOE, the major costs and possible cost reductions. A sensitivity analysis has been performed to identify the variability of the LCOE as a function of the various cost sources. A comparison between the reference case and alternative solutions has been included.

2. The UGEN concept:

2.1. Background

2.1.1. Salter’s Duck

The UGEN external floater was inspired by Salter’s duck WEC concept. Salter’s duck is a wave energy device that has been widely studied. It was invented by Stephen Salter in 1974 in Edinburgh University but has been abandoned mainly due to the lack of efficient power take off (PTO) mechanism. The aim of this device is to absorb the maximum amount of the wave energy resource available from a hydrodynamic efficiency perspective. The Salter’s duck extracts wave energy from the pitch movement [6, 7]. The energy from waves passing through a vertical plane is concentrated close to the surface and the water movements at all depths are at the same phase. The device was inspired on a simple vertical vane pivoting about a horizontal axis along its bottom edge. This primary device rotates with hydrodynamic efficiencies about 40% for a specific sea state, which means it can extract mechanical energy, up to the 40% of the energy available of the waves. But this efficiency could be increased if the designed shape does not displace water astern and so the amount of water displaced at any depth correspond to the amplitudes of water movements at that depth. This led to the present design of the Salter duct shown in Figure 2.1, which is able to reach a peak efficiency of over 80% [6].

The shape shown in Figure 2.1 rotates about its centre O, and absorbs power from waves coming from the right. The stern is a half cylinder centred at O, but from the bottom point it grows into the surface as another cylinder centred about O’. This shape continues until it reaches an angle θ, to the vertical, at which point it develops into a tangent, which is continued above the surface [6].

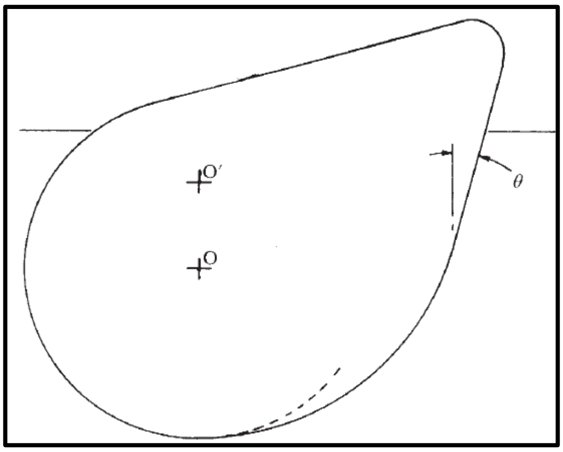


Figure 2.1. Shape of Salter's duck vane. The device rotates about O due to incoming waves. Wave come from the right.

On the one hand, the Salter’s duck, see Figure 2.1 is facing the incoming wave inducing a pitch motion. It should be noticed that when the vane rotates there is no change in the displacement of the water behind it due to the cylinder shape in the astern part. For the Salter duct to be efficient it needs to reflect most of the incoming wave and so it needs a relatively high draft.

On the other hand, in the UGEN, see Figure 2.8, the vertical side is facing the incoming wave, while the edge (asymmetrical part) is facing downstream the wave. For this to be efficient the wave reflection needs to be small, this requiring a small draft of the device. In an ideal situation, the incoming wave from the right would be cancelled on the left by the asymmetrical radiated wave, showing no wave on the downstream side of the wave. As transmission and radiation waves are not zero, they need to have identical amplitudes and opposite phases. Addressing to the ideal situation mentioned, the energy available of the wave would be completely absorbed by the device, this statement should be confirmed by checking if there is no wave on the down wave side.

Salter's duck extracts energy through the relative motion between the hull and an internal body. The main difficulty was related to this internal body as a good solution for it was never found. In Annex C information about the different phases of PTO development is presented. As it has been mentioned, the UGEN shape was inspired by the shape of the Salter's duck. Finally, the internal part of the UGEN was inspired by the U-tank of the vessels.

2.1.2. Wells turbine & other air turbines

OWC WECs exploit the flow resulting from pressure variations of the air to produce electricity. The transformation from pneumatic power to electricity is most commonly achieved by an air turbine coupled to an electrical generator.

Conventional unidirectional flow turbines can be used to equip OWCs (with a rectifying system with non-return valves) but they are not suitable for large air flows [8]. Due to this limitation self-rectifying turbines are the most used solution in OWCs. Self-rectifying turbines are the ones that rotate in the same direction regardless the flow direction.

Most self-rectifying turbines are axial-flow machines. Two basic types which have been considered and used until now for OWC devices are the Wells turbine (1976) and the impulse turbine (1975).

Considering the Euler turbomachinery equation [9] the power of the turbine can be computed from the air velocities in the entrance and in the exit of the turbine rotor, see equation (2.1).

$$E = \Omega \cdot (r_1 V_{t1} - r_2 V_{t2}) \tag{2.1}$$

- E [J/kg]: Energy per unit mass of circulating fluid (air).
- Ω [rad/s]: Rotational speed of the air turbine.
- r_1, r_2 [m]: Radial coordinates of the inlet and outlet rotor sections, respectively.
- V_{t1}, V_{t2} [m/s]: Tangential flow velocity in the rotor entrance and exit, respectively.

Specifically, for an axial-flow turbine rotor, with mean radius $r_1 = r_2 = r$, the equation results as (2.2).

$$E = \Omega \cdot r \cdot V_x (cot\alpha_1 - cot\alpha_2) \tag{2.2}$$

- V_x [m/s]: Axial component of the flow velocity.
- $cot\alpha_i = V_{xi}/V_{ti}$, angle between the axial and tangential velocity components.
- V_{x1}, V_{x2} [m/s]: Axial flow velocity in the rotor entrance and exit, respectively.

Equation (2.1) shows that the flow has to be deflected by the rotor blades in such way that $V_{t1} > V_{t2}$ as axial turbines have the same average inlet and outlet radius.

Wells turbine

A Wells turbine rotor consists of several symmetrical aerofoil blades positioned around a central hub with their chord line normal to the axis of rotation, as shown in Figure 2.2.

From classical aerofoil theory, fluid flow at an angle of incidence, α, will generate a lift force, *L*, normal to the free stream, and a drag force, *D*, in the direction of the free stream. These forces can be resolved into a tangential component, F_t, which creates a torque around the axis of the turbine, and an axial component, F_x, which causes a thrust along the axis of the turbine, as shown in Figure 2.2, [10].

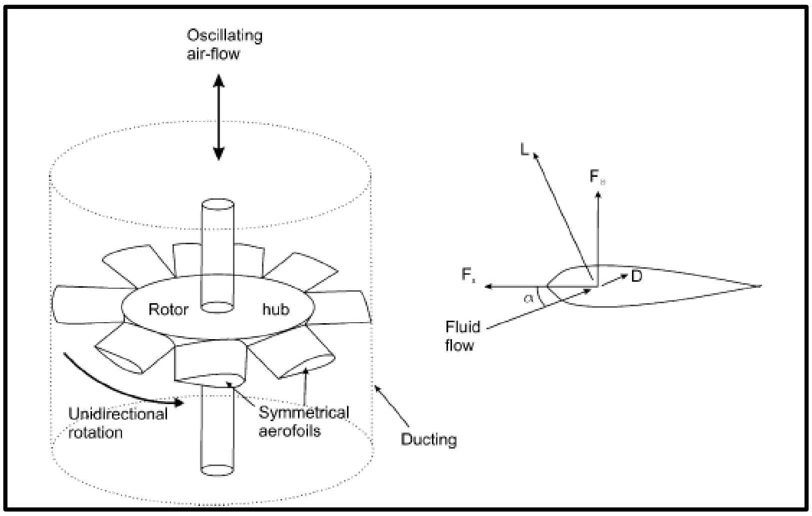


Figure 2.2. The wells turbine drawing and diagram of forces [10].

In Figure 2.3 a Wells turbine with guide vanes is shown. It can be noticed that the guide vanes redirect the flux in order to avoid losses in the outgoing flux due to tangential velocity (they allow to recover the otherwise lost kinetic energy).

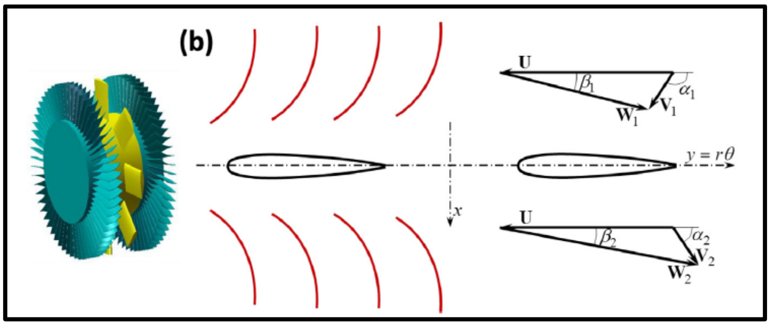


Figure 2.3. Velocity diagram of a Wells turbine with vanes. V [m/s] absolute flow velocity, W [m/s] relative flow velocity, U [m/s] rotor blade velocity.

An important characteristic of Wells turbine is that the exit angle, α_2, depends only on the entrance angle, α_1, and on the rotor chord-to-pitch ratio *c/t* not on the flow rate or the rotational speed. Above, *c* is the rotor blade chord and *t* the rotor blade pitch.

	Mighty Whale [11, 12]	**LIMPET plant** [11]	**Pico pant** [13]
Power output	30 kW	250 kW	400 kW
Type	Wells turbine with guide vanes	Contra rotating Wells turbine	Wells turbine. Monoplane, fixed blades.
Configuration	Tandem	-	-
Radium	1.7 m	2.6 m	2.3 m
Blades	NACA0021	NACA0021	NACA0015
Number of blades per rotor	8	7	8
Weight	480 kg	-	-
Max. RPM	1,800	1,400	1,500

Table 2.1. Specifications of the Wells turbine installed in the Mighty Whale and LIMPET plant.

The energy can be obtained directly from the equation (2.3).

$$E = 2 \cdot \Omega \cdot r \cdot V_x \cdot tan\frac{\pi \cdot C}{2 \cdot t} \qquad (2.3)$$

It can be seen in (7) that the work per unit mass done by a rotor increases with the chord-to-pitch ratio *c/t*. Although this ratio cannot be too close to unity due to increase flow blockage.

There have been different rated power Wells turbines, from approximately 20 kW to 500kW.

The specifications of three installed Wells turbine are shown in Table 2.1.

Axial-flow self-rectifying impulse turbine

The geometry of the rotor blades of this turbine is a modified version of the classical steam turbine of impulse type. It consists of a rotor with symmetrical blades with guide vanes in the inlet and outlet, see attached Figure 2.4. It can be noticed that the exit angle of the guide vane is almost equal to the inlet angle in the rotor blades.

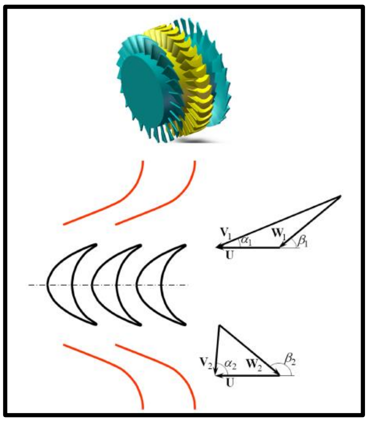


Figure 2.4. Self-rectifying impulse turbine. Rotor with twin guide vane system

An incompatibility situation arises from this system, one cannot have simultaneously the right flow incidence at the rotor blades and at the second guide-vane row. To solve the excessive incidence problem, guide vanes of variable geometry have been proposed by allowing the vanes to pivot under the action of the aerodynamic moments (depending on air flowing inwards or outwards).

Wells turbine and axial-flow impulse turbine comparative

In Table 2.2, a comparative between the Wells turbine and axial-flow impulse can be seen.

Wells turbine	Self-rectifying impulse turbine
Advantages	**Advantages**
- High peak efficiency, 75%. - Much higher rotor speed. - Lager capacity for energy storage by flywheel effect due to higher rotational speeds. - Higher speed electrical generators result in smaller and lighter equipment.	- Flow range is wider. See Figure 2.5.
Disadvantages	**Disadvantages**
- Narrow flow range: for increasing flow rate, the efficiency drops when stalling at rotor blades occurs. Figure 2.5. - Efficiency more sensitive to changes in Reynolds number.	- Large aerodynamic losses due to excessive incidence flow angle at the entry to the second row of guide vanes. - Low peak efficiency, 50%. With guide vanes of variable geometry peak up to 60%. - Loss associated to axial flow cannot be avoided: it needs a diffuser.

Table 2.2. Comparative advantages and disadvantages between Wells turbine and self-rectifying impulse turbine.

The Figure 2.5, shows the narrower flow range of the Wells turbine compared to the self-rectifying turbine due to stalling at the rotor.

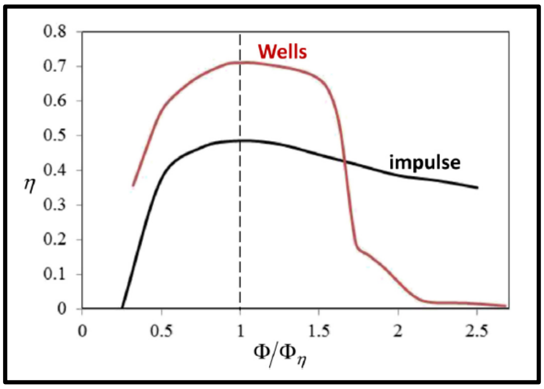


Figure 2.5. Efficiency versus flow coefficient ratio ϕ/ϕ_η for a monoplane Wells turbine with guide vanes and an impulse turbine with fixed guide vanes. ϕ_η denotes the peak efficiency conditions [14].

Bi-radial turbine

As said before, Wells turbine and self-rectifying axial-flow present some characteristics not optimal for an OWC device. The bi-radial is a novel turbine being studied in order to improve the response of OWCs mechanisms. The bi-radial turbine [15],

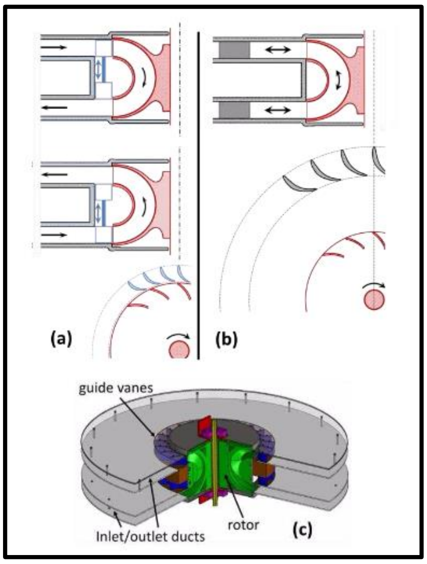


Figure 2.6, is an impulse turbine that is symmetrical with respect to a plane perpendicular to its axis of rotation. The flow into, and out of the rotor is radial. The rotor is surrounded by a pair of radial-flow guide-vane rows; each row being connected to the corresponding rotor inlet/outlet by a duct whose walls are flat discs.

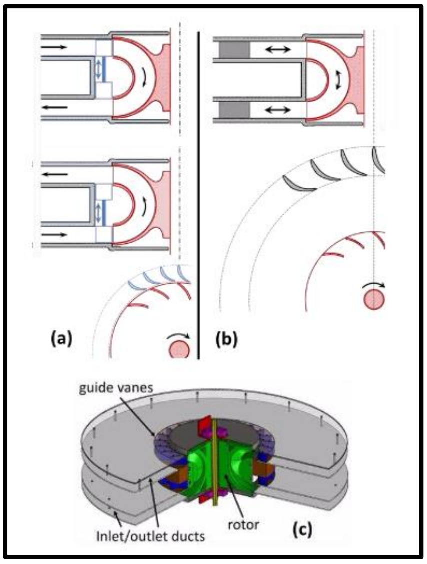


Figure 2.6. Biradial turbine: (b) version 1 with radially-offset fixed guide vanes; (a) version 2, with axially-sliding guide vanes; (c) perspective view.

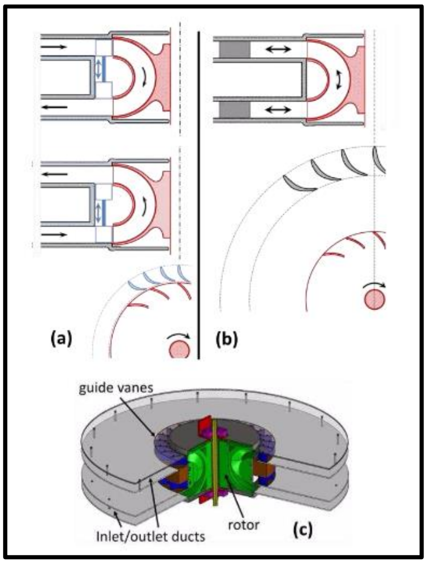
In version 1, 

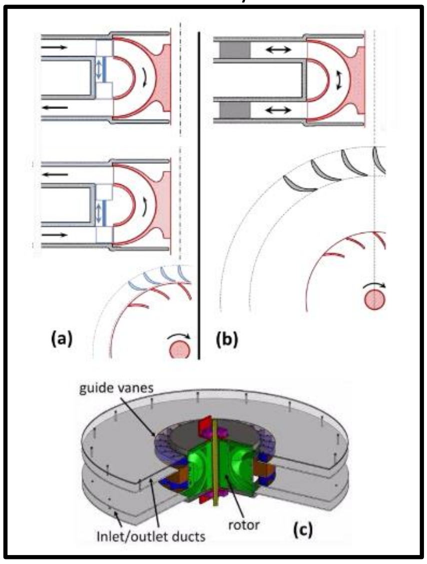
Figure 2.6 (a), the guide vane rows may be removed from, or inserted into, the flow space by axially displacing the whole guide vane set, so that the downstream guide vanes are prevented from obstructing the flow coming out of the rotor. The version 1 was studied in [16, 17] were the peak efficiency was found to be about 79%, the highest efficiency of a self-rectifying air turbine. In version 2, as a way of reducing the losses due to excessive incidence at the entry to the second row of guide vanes, the guide vanes are radially offset from the rotor 

Figure 2.6 (b).

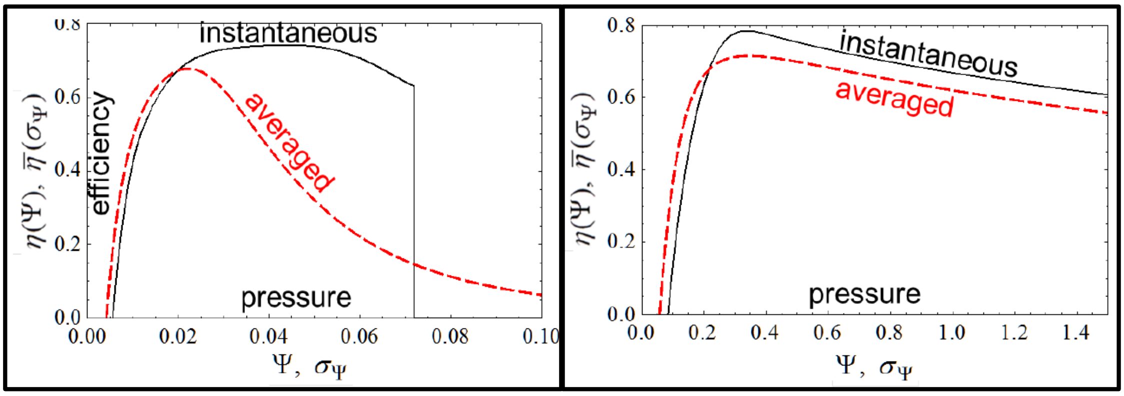


Figure 2.7. Efficiency versus pressure coefficient, Ψ. On the left a Wells turbine and on the right a biradial turbine [15].

In Figure 2.7 it can be seen the higher efficiency of the biradial turbine, up to 79% and the wider range of working pressure without a significant efficiency drop. The averaged curves assume sinusoidal flow conditions between plus and minus each flow rate.

2.1.3. Patents and previous work – literature review

The UGEN concept has been patented by Ribeiro e Silva et. al, [19], in 2010 with a sponsorship from IST. The device was patented at the "Instiuto Nacional da Propiedade Industrial (INPI)" with the title "Dispositivo flutuante assimétrico conversor de energia das ondas" with the reference nº 105368.

The following information was extracted from [20].

In 2010 an experimental program with a 1:16 scaled model of the UGEN wave energy converter was carried out at IFREMER, France, in both regular and irregular waves. The objective was to obtain insight in the dynamics of the device and also to obtain experimental data to assess the validity of a numerical model to represent the hydrodynamic wave-body interactions.

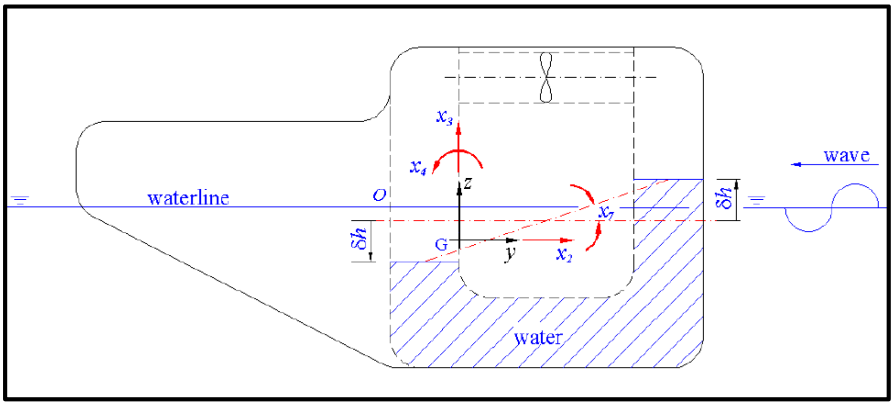


Figure 2.8. UGEN device diagram showing the coordinate system.

In Figure 2.8 the coordinate system of the UGEN device is shown. The degrees of freedom are sway (x_2), heave (x_3), roll (x_4) and the motion of the water in the U-tank (x_7).

The experimental results show two distinct frequency ranges with large dynamic amplification of the fluid motion in the U-tank (oscillating water column). The first is related to the natural period of the oscillating water column itself and the second one occurs around the rolling motion natural period. The two peaks of the tank transfer function are beneficial in irregular waves since they widen the frequency range where wave energy is captured. The sway motion is strongly coupled to the U-tank motion and there is also a small coupling between the U-tank motion, heave and roll. Both the sway and heave are coupled to the rolling motion. For these reasons UGEN has the potential to extract wave energy from these three modes of rigid body oscillation. Another conclusion achieved is that increasing the damping of the power take off system (PTO) decreases very much the oscillations of the water in the U-tank and there is a small decrease in the peaks of the roll and heave transfer functions.

It was also proven that the Wamit model with internal U-tank is able to predict properly the coupling effects between the U-tank motions and the sway, heave and roll motions. However, Wamit does not provide the free surface elevation in the U-tank and so it is not possible to estimate the extraction of energy from the U-tank motions. Regarding the simplified Lloyd model to represent the dynamics of the water in the U-tank, it overestimates its natural period, which is reflected on the transfer function of the U-tank water motions and also on the coupling with the rigid body motions.

The numerical predictions underestimate the sway motions between 8s and 9s of wave period. The increase of the U-tank damping reduces the rolling resonance peak, however this effect is overestimated by the numerical model. For these reasons, it was concluded that the numerical model of the WEC dynamics needs to be improved. Although the results shown have been obtained by the numerical model and the device being tested in the laboratory was a scaled model, the conclusions are representative of the full scale device. The mean power extracted [kW/m] in regular waves, estimated by the numerical model, shows three peaks distributed between 4 and 8 seconds of wave period, see Figure 2.9. This means that the device has a good potential to work efficiently in multi-frequency sea states (realistic sea states). The peaks are related to the natural periods of the U-tank, heave and roll motion. It can be also noticed that the power absorption depends on the damping factor of the PTO.

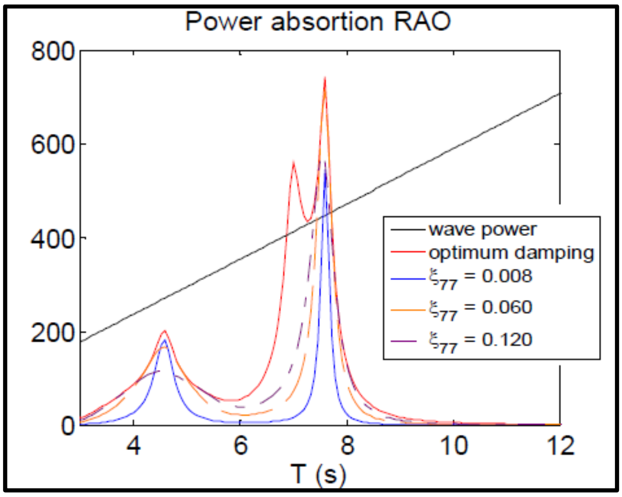


Figure 2.9. Numerical transfer function of the wave power absorbed [kW/m] in harmonic waves as function of the wave period. Three PTO damping coefficients of the fluid motion in the U-tank were considered. The red line stands for the power extracted with the optimum setting of the PTO damping which is frequency dependent. The black line represents the mean wave power for a wave from with the same width as the WEC (15m).

2.2. System description: main internal components

The UGEN WEC is an asymmetric floating body with a large interior U-tank partially filled with water. The energy is extracted from the oscillations of the U shaped water column and these oscillations are excited mainly by the rolling of the floater, see Figure 2.10.

The lateral reservoirs of the U tank are partially filled with water and the remaining with air. The two lateral air compression chambers are connected by a tube with a reversible turbine inside. The relative motion between the floater and the water column forces the air through the turbine which extracts the energy [21].

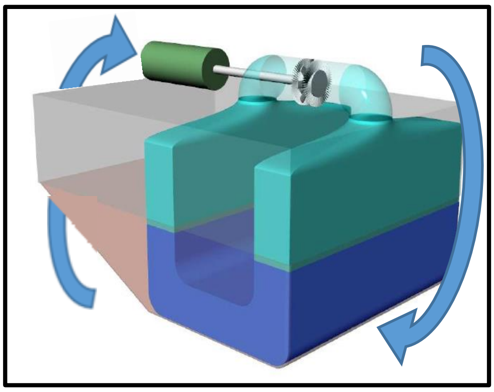


Figure 2.10. Perspective view of UGEN energy converter. The main degree of freedom of the UGEN, rolling, is represented with blue arrows.

The UGEN is kept in station with a slack mooring system and is characterized by two main natural periods, the rolling natural period and the U-shaped oscillating water column natural period. If these two periods coincide, then the tank works as a roll stabilizing device. It is advantageous to separate the two natural periods, which means to reduce the period of the tank with respect to the roll natural period. The ideal separation interval requires investigation.

The linear dynamics of the system can be represented in the frequency domain by a set of four coupled differential equations of motion (sway (x_2), heave (x_3) and roll (x_4) motions of the floater, plus the motion of the water in the tank (x_7)) [22].

The design variables are the floater main dimensions, the U-tank dimensions and shape, the turbine characteristics and device mass distribution for deployment in Leixões, see Table 2.3 and Table 2.4. The optimization process is explained in "UGEN mathematical model and its validation with experimental data" [22]. As the first device has been designed to be deployed in Aguçadora, the met-ocean conditions considered in the latest optimization are from Leixões, a location sufficiently near Aguçadora, 35km, for the wave resource to be very similar. Depending on the location, the dimensions of the UGEN will be adapted to minimize the LOCE.

Dimensions of the floater	
Ln (width) [m]	31.176
Bm (length) [m]	19.957
T (draft) [m]	13.753
H (height) above water [m]	5.000
Total Mass [tonnes]	6,620
U tank water mass [tonnes]	1,020
Ballast mass (water) [tonnes]	5,190
Steel structure mass [tonnes]	410
Tn (tank) [s]	5.458
Tn (roll) [s]	13.944

Table 2.3. Dimensions of the floater for deployment in Leixões considering the power generated divided to the amount of steel as the objective function of the design optimization.

As can be seen in Table 2.3, the steel structure mass refers to the total structural weight of the device, 410 tonnes. In operating mode, the ballast system of the device is filed with sea water in order to modify the total mass and natural period of the UGEN to maximize the electrical generation. The system is mentioned in Table 2.5 as ballast system (operation condition). The total mass in operating mode is 6,620 tonnes.

In Table 2.5 it can be also seen the ballast system (submergence). A possible solution that has been proposed to reduce the robustness and structure mass is the possibility to submerge the device during extreme meteor conditions by filling a second ballast system. This possibility is in an early stage and will require further studies to evaluate the viability and economic profit if it is implemented.

Characteristics of the turbine	
N (rotational speed range) [rad/s]	125 - 300
Dt (turbine diameter) [m]	2,75 m

Table 2.4. Characteristics of the turbine for deployment in Leixões.

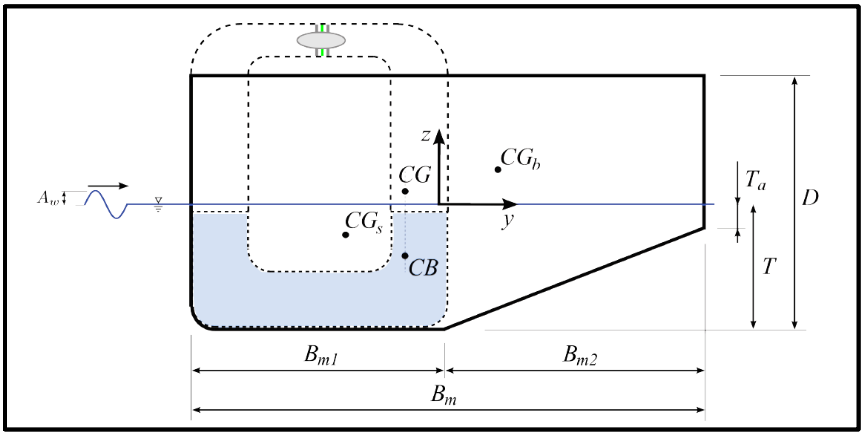


Figure 2.11. Cross-section view of the UGEN, where the origin of the body coordinate system Oxyz, the centre of gravity CG, the centre of buoyancy CB, and main dimensions' length Ln, beam Bm, draught T, and depth D, are shown.

The main components of the UGEN are the following:

Main Group	Sub group
Main structure	Hull
	U-type tanks
	Air duct
	Superstructure
Mooring system	Mooring cable
	Anchor
Electrical power generation system	Generator
	Command & control system
	Switch board
	Electric cables
Ballast system	Fresh water inside the U-tanks
	Ballast piping
	Ballast pump
	Valves
	Gates
Power-take-off (PTO)	Wells turbine
	Shaft line
	Air valves
Hull appendages	Cathodic protection

	Sea chests
	Coating (painting scheme)
Nautical indicators	Mast
	Navigation lights
	Radar reflectors
Ballast system (operational condition)	Ballast tank #1
	Ballast tank #2
	Ballast tank #3
Ballast system (submergence)	Ballast tank #4
	Ballast tank #5

Table 2.5. Main components of the UGEN.

The Table 2.5 presented above is an initial hypothesis of components and parts that will constitute the UGEN.

2.3. UGEN mathematical model and its validation with experimental data

The following information was extracted from [22].

Floating body hydrodynamics

The hydrodynamic forces and motions have been represented on a Cartesian coordinate system with origin on the gravity centre (CG) of the floating body, as shown in Figure 2.8. y is the longitudinal horizontal axis so that waves propagate in the positive y-axis direction, *z* is positive upwards and *x* is perpendicular to the former. All degrees of freedom, x_j, $j = 1, \ldots, 6$, are sequentially numbered according to the standard convention. The vertical motion of the water in the U-tank reservoirs, ∂h, is represented by an additional rotational degree of freedom x_7 as represented in Figure 2.8 and Figure 2.12.

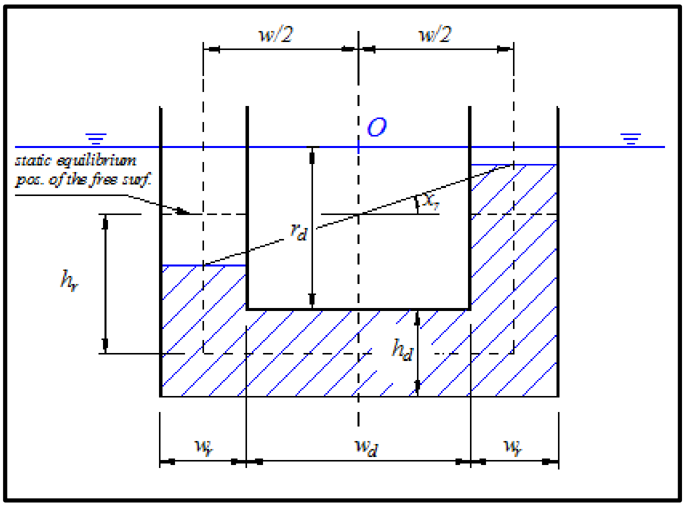


Figure 2.12 U-tank dimensions, using same nomenclature as passive U-tank of Lloyd's (1989) method.

The results of the simulated model in [22] are the added mass (A_{kj}) and damping coefficients (B_{kj}) for the six Degrees-of-Freedom (DoFs) rigid body motions ($x_j, j = 1, \ldots, 6$), as well as the wave exciting forces in harmonic waves ($F_k^E(t)$) along the six directions of the coordinate system ($k = 1, \ldots, 6$). See the generic equation (2.4).

$$(m_{kj} + a_{kj})\ddot{x}_{kj} + b_{kj}\dot{x}_k + c_{kj}x = F_k^E \quad (2.4)$$

Modelling of the U-tank oscillating water column

The dynamics of the 7th DoF, consisting on the rotation of the oscillating water column in the U-tank, is represented by a simplified model based on the one-dimensional Euler equation. Consider the U-tank of Figure 2.12 with two lateral reservoirs with constant rectangular cross section and a connecting duct with constant rectangular cross section as well. The length of the tank in the perpendicular to the cross section is L_t. The water column oscillations are induced by the roll and sway motions of the floater, see Figure 2.8.

The fluid velocity inside the U-tank, v, has the direction of the y^*-axis, see Figure 2.11, and the acceleration effects on the corners are neglected. The motion of the fluid is governed by the one dimensional Euler's equation, see (2.5).

$$\frac{\partial y}{\partial t} + v\frac{\partial v}{\partial y^*} = F_{y*} - \frac{1}{\rho_t}\frac{\partial p}{\partial t} \tag{2.5}$$

- F_{y*}[N/kg]: external force per unit mass acting on the fluid.
- ρ_t [kg/m³]: fluid density.
- p [Pa]: pressure.
- t [seconds]: time.

Since the fluid acceleration on the corners is neglected the spatial derivate of the fluid is zero, that means the second term on the left of the equation $\left(v\frac{\partial v}{\partial y^*}\right)$ can be deleted.

Assuming that the free surface in the reservoirs move as a piston the fluid velocity in the reservoirs can be related to the angular velocity, $\ddot{x}_7$.

The external force, F_{y*}, represented in (2.5) has different contributions. First contribution from the acceleration of gravity (the related forces change with the angular motions), a second contribution related to the accelerations of the floater motions and the third component representing the frictional forces inside the tank. Representing the force in (2.5) in terms of the unknown floater motions, and integrating the resulting differential equation with respect to y^*results on the equation of oscillatory fluid motion inside the tank as function of the pressure difference between the two reservoirs. Finally, the equation of the oscillating water column is given by the equation (2.6).

$$A_{77}\ddot{x}_7 + B_{77}(\dot{x}_7 - \dot{x}_4) + C_{77}x_7 + A_{72}\ddot{x}_{2+}A_{74}\ddot{x}_4 + C_{74}x_4 = 0 \tag{2.6}$$

Where $A_{77}, B_{77}, C_{77,} A_{72}, A_{74,} C_{74}$ are hydrodynamic coefficients depending of the angular velocity, the coefficient of resistance of the tank to the water motion, the acceleration of gravity, the density of the fluid inside the tank and the length of the tank in the direction perpendicular to the cross section.

Modelling of the self-rectifying air turbine

The relation between the instantaneous pressure difference $p(t)$ across the turbine and the instantaneous mass flow rate of air $\dot{m}$ passing through the turbine depends directly on the air turbine characteristics. The turbine characteristics can be expressed by non-dimensional coefficients of pressure (Ψ), flow rate (ϕ) and turbine power output (Π) that depend on:

- ρ_t [kg/m³]: density of the fluid inside the tank.
- N [rad/s]: rotational speed.
- d_t [m]: turbine diameter.

It has been shown that the Wells turbine exhibits a linear relation between pressure difference and the mass flow rate as can be seen in the equation (2.7).

$$\dot{m}(t) = \frac{K_t d_t}{N} p(t) \tag{2.7}$$

- $\dot{m}(t)$ [kg/s]: mass flow rate.
- K_t [dimensionless]: constant depending on the turbine geometry, and not its dimensions.
- N [rad/s]: rotational speed.
- $p(t)$: pressure difference.
- d_t [m]: turbine diameter.

Equations of motion

DoFs that will be excited by these waves are sway (x_2), heave (x_3), roll (x_4) and the motion of the water in the tank (x_7). These equations are coupled with equation of the Wells turbine, (2.7). The following are the set of, equations required to provide a solution:

$$(M + A_{22})\ddot{x}_2 + B_{22}\dot{x}_2 + A_{23}\ddot{x}_3 + (A_{24} - M_{zG})\ddot{x}_4 + B_{24}\dot{x}_4 + A_{27}\ddot{x}_7 + pA_t = F_2^E(t) \tag{2.8}$$

$$A_{32}\ddot{x}_2 + B_{32}\dot{x}_2 + (M + A_{33})\ddot{x}_2 + B_{33}\ddot{x}_3 + C_{33}x_3 + (A_{34} - M_{yG})\ddot{x}_4 + B_{34}\dot{x}_4 + C_{34}x_4 = F_3^E(t) \tag{2.9}$$

$$(A_{42} - M_{zG})\ddot{x}_2 + B_{42}\dot{x}_2 + (A_{43} - M_{yG})\ddot{x}_3 + B_{43}\dot{x}_3 + C_{43}x_3 + (I_{44} + A_{44})\ddot{x}_4 + B_{44}\dot{x}_4 + B_{44ext}\dot{x}_4 + C_{44}x_4 - A_{47}\ddot{x}_7 + C_{47}x_7 - pA_t d_t = F_4^E(t) \tag{2.10}$$

$$A_{77}\ddot{x}_7 + C_{77}x_7 + A_{72}\ddot{x}_2 + A_{74}\ddot{x}_4 + C_{74}x_4 - pA_{tk}w = 0 \tag{2.11}$$

$$\frac{V_o}{c_a^2}\dot{p} + \frac{K_t d_t}{N} p - A_{tk} w p_a (\dot{x}_7 - \dot{x}_4) \tag{2.12}$$

The added mass A_{kj}, damping coefficient B_{kj} and wave exciting force $F_k^E(t), k, j = 2, 3, 4$ are determined using WAMIT.

Afterwards, the equations of motion can be solved in the frequency domain to obtain the motions transfer functions and the pressure transfer function. This numerical model assumes that the pressure distribution in the interior free surface is uniform and the interior wave effects are neglected. Furthermore, linearity is assumed for the floater motion, oscillating water column motion and pressure fluctuation. The translational motions are also supposed to be small enough to not be considered.

Power extraction in random waves

The energy extraction from the floating device under irregular wave conditions is modelled using a stochastic method, as presented in [23]. One of the main advantages of the UGEN concept relies in its simplicity (no external moving parts or articulations) associated with the fact that no direct hydrodynamic interaction will occur between the internal OWC and the floater itself. These characteristics lead to a higher level of confidence of the obtained numerical predictions of annual averaged power by the UGEN.

It has been assumed that a given sea state is represented by the superposition of regular wave components, each with its own amplitude, frequency and random phase angle. This assumption implies that the wave elevation can be described as a stationary, ergodic and Gaussian process. The theory used was developed by Longuet-Higgins [24].

Optimization overview

The optimization problem is particular focused in the generic geometrical characteristics of the UGEN in order to maximize the energy extracted from the waves. To achieve this objective, the natural period of oscillation of the U-shaped interior water column is designed to be shorter than both the characteristic wave period, and natural roll period of the hull floating structure to avoid anti-roll stabilization effect.

Some important parameters that are likely to influence the power extraction should be analysed as follows: shape of floater (induced forces and moments on the hull, restoring forces, added inertia, radiation damping), turbine efficiency (damping effect, turbine diameter and rotational speed), position of the centre of gravity (specifically vertical coordinate z_g) and the roll moment of inertia about the centre of gravity I_{44}.

The roll natural period is characterized for the following equation (2.13):

$$T_{n,4} = 2\Pi\sqrt{\frac{I_{44}+A_{44}}{\rho_w z_g(I_{xx}/\nabla+z_b-z_g)}} \tag{2.13}$$

- I_{44} [kg·m²]: Roll moment of inertia about the centre of gravity.
- A_{44}[kg·m²]:]: Added inertia.
- ρ_w [kg/m³]: Density of the water inside the tank.
- I_{xx} [m^4]: Second moment of area about x-axis.
- ∇ [m³]: Displaced volume.
- z_b [m]: Position of centre of buoyancy, vertical coordinate.
- z_g [m]: Position of centre of gravity, vertical coordinate.

Design parameters and objective function

The optimization of the UGEN is focused on the maximization of the annual averaged power extraction divided a representation of the total cost (as a first approach computed as the total mass of steel). This depends of the hull geometry and the PTO equipment and other characteristics that affect the system dynamics. The optimization has been divided into two: main optimization problem and internal optimization problem. For the main optimization problem, it has been considered only the geometrical characteristics of the hull presented in Figure 2.11 (T, L_n, B_m). On the other hand, for the internal optimization problem it has been optimized the turbine, roll mass moment and vertical positon of the centre of gravity (d_t, N, I_{44}, z_g). The objective function is defined as the ratio between the annual-averaged power output and the device mass of steel.

$$f_o(x) = \frac{\bar{P}_{ann}}{m_{st}} \tag{2.14}$$

- $\bar{P}_{ann}$[W/year]: Annual-averaged power output.
- m_{st}[kg]: mass of steel.

The climate specification has been based on long-term statistical data analysis off the Portugal west coast. This design-point corresponds to the Pilot Zone of S. Pedro de Moel. This means that the optimization is the suitable for this particular location but there is evidence that it will not be significantly different for Aguçadoura.

Results

As said before the optimization problem of the annual averaged power output is divided into two parts. A main problem with the floater main dimensions and an internal problem, where the turbine characteristics and device mass distribution are optimized. For the internal optimization, the objective function can be simply defined as the annual-averaged power output $\bar{P}_{ann}$, since the geometrical characteristics of the device and its mass, are fixed.

Finally, the results that have been obtained are shown in “System description: main internal components”.

2.4. Performance data: power matrix

The optimization presented in the chapter above has allowed to specify the dimensions that maximize the annual-averaged power divided for the mass of steel of the device.

An important tool to analyse the electric generation of WECs for specific incoming sea states is the power matrix. As said in 1, the sea state is characterized in its simpler form by two parameters: the significant wave height and the wave (energy or peak) period. More advanced descriptions include directional characteristics, typical spectral shapes, etc.

The power matrix shows the average power generated for the UGEN for each sea state, defined by bins of wave height and period independent values. The power matrix of the UGEN with geometry optimized for deployment in S. Pedro de Moel and using a Wells turbine with an efficiency modelled following the reference [43]. is presented in Table 2.6. The power shown in the bins of the power matrix is the power in the shaft of the turbine, the losses of the power chain (alternator, wire, transformer, distribution…) are not included. Inside the table the power generation is given in [kW]. It can be seen i.e. that for a significant wave height of 4.5m (row) and period of 7,5s (column) the power generation is 390.041 kW while for a significant wave height of 0.5m (row) and period of 4.5s (column) the power generation is zero.

Power Matrix in kW														
		Te [s]												
		4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	16,5
Hs [m]	0,5	0,00	0,00	0,00	0,02	0,07	0,07	0,03	0,01	0,00	0,00	0,00	0,00	0,00
	1,5	0,01	0,14	7,24	29,32	43,41	43,22	35,41	25,85	17,42	10,96	6,47	3,57	1,83
	2,5	1,47	5,75	48,33	122,68	162,87	162,35	140,45	112,21	85,37	62,83	45,06	31,58	21,61
	3,5	9,39	23,66	118,28	252,96	316,61	315,83	281,81	235,43	188,44	146,54	111,76	84,03	62,48
	4,5	25,22	52,72	207,25	390,04	465,81	464,91	425,05	368,14	306,91	248,70	197,39	154,40	119,53
	5,5	47,96	90,96	304,15	500,00	500,00	500,00	500,00	491,28	423,22	355,10	291,71	235,71	188,14
	6,5	76,59	136,62	399,64	500,00	500,00	500,00	500,00	500,00	500,00	455,93	385,59	320,61	262,95
	7,5	110,27	187,78	488,42	500,00	500,00	500,00	500,00	500,00	500,00	500,00	473,59	403,49	338,95
	8,5	148,12	242,27	500,00	500,00	500,00	500,00	500,00	500,00	500,00	500,00	500,00	481,08	412,55
	9,5	189,11	298,04	500,00	500,00	500,00	500,00	500,00	500,00	500,00	500,00	500,00	500,00	481,71
	10,5	232,14	353,43	500,00	500,00	500,00	500,00	500,00	500,00	500,00	500,00	500,00	500,00	500,00

Table 2.6. Power matrix of the UGEN optimized configuration, for sea states defined by a two-parameter Pierson-Moskowitz spectrum. The vertical axis shows the significant height of the waves. The horizontal axis shows the energy period of the waves. The time-averaged power is given in [W]. Optimized geometry is obtained through out the maximization of the annual-averaged power output using COBYLA algorithm.

3. LCOE mathematical formulation

Once the UGEN concept has been exposed, this chapter provides a detailed explanation about what is the Levelised Cost Of Energy (LCOE), why is it an important tool for novel technologies and how is it calculated.

3.1. Annual energy production

The Annual Energy Production (AEP) is the yearly amount of energy delivered by a power plant during its useful life.

The power produced by ocean energy technologies is directly dependent on the available resource. The sea-state are typically defined by two spectral parameters: the significant wave height, Hs and the wave peak period, Tp. Although these values (Hs and Tp) give a satisfying statistical representation of the sea-state conditions over a certain period of time (typically three hours), it should be noted that they do not correspond to each wave observed on a wave-by-wave basis. Consequently, the power produced by a WEC is not constant over time.

The critical factors influencing the AEP of offshore renewables are, [25]:

- The local energy resource available wave power: the amount of wave energy available for capture, depending on the wave height and period. To characterise the available resource 3 steps are usually carried out: collect existing statistical resource data, local resource acquisition campaign at least for one year and due-diligence re-analysis of the resource assessment (required by financiers).
- The performance of the converter. The efficiency with which a particular device converts wave energy into useful electricity is primarily a function of the sea state. Nameplate, adaptability to local environmental conditions, losses throughout the conversion chain and availability are other important factors to consider when calculating the AEP.

To compute the AEP, both the local energy resource and the technology performance need to be characterised. These two data are specified through matrices. Both matrices are divided into cells which represent the sea states (wave period parameter in one axis and wave height parameter in the other). The scatter diagram (or local energy resource matrix) shows the probability of occurrence of each sea-state for a given location, while the device power matrix shows the average power the WEC is expected to produce for each sea-state.

Frequency of ocurrence in %													
	Te [s]												
Hs [m]	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	16,5
0,5	0,07	2,41	2,21	0,33	0,01	0	0	0	0	0	0	0	0
1,5	0,03	6,26	17,18	13,02	7,42	2,67	0,39	0,13	0	0	0	0	0
2,5	0	0,23	3,16	5,78	7,1	6,3	3,65	1,12	0,18	0,01	0	0	0
3,5	0	0	0,03	1,17	2,79	3,2	2,47	1,22	0,39	0,11	0	0	0
4,5	0	0	0	0,01	0,64	1,43	1,45	1,06	0,51	0,18	0,02	0	0
5,5	0	0	0	0	0	0,36	0,83	0,61	0,33	0,07	0,03	0	0
6,5	0	0	0	0	0	0	0,17	0,34	0,18	0,06	0,05	0	0
7,5	0	0	0	0	0	0	0,03	0,07	0,13	0,05	0,02	0	0
8,5	0	0	0	0	0	0	0	0,01	0,05	0,09	0,03	0	0
9,5	0	0	0	0	0	0	0	0	0,03	0,05	0	0,01	0,01
10,5	0	0	0	0	0	0	0	0	0	0,01	0,01	0	0

Table 3.1. The scatter diagram for Leixões is plotted, it shows the probability of ocurrence, in percentage, of each sea state. In the vertical axis the wave significant height parameter is placed while in the horizontal axis the wave period parameter is shown.

Power Matrix in kW														
		Te [s]												
		4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	16,5
Hs [m]	0,5	0,00	0,00	0,00	0,02	0,07	0,07	0,03	0,01	0,00	0,00	0,00	0,00	0,00
	1,5	0,01	0,14	7,24	29,32	43,41	43,22	35,41	25,85	17,42	10,96	6,47	3,57	1,83
	2,5	1,47	5,75	48,33	122,68	162,87	162,35	140,45	112,21	85,37	62,83	45,06	31,58	21,61
	3,5	9,39	23,66	118,28	252,96	316,61	315,83	281,81	235,43	188,44	146,54	111,76	84,03	62,48
	4,5	25,22	52,72	207,25	390,04	465,81	464,91	425,05	368,14	306,91	248,70	197,39	154,40	119,53
	5,5	47,96	90,96	304,15	514,86	593,85	592,94	551,83	491,28	423,22	355,10	291,71	235,71	188,14
	6,5	76,59	136,62	399,64	621,76	699,29	698,40	658,37	598,14	528,38	455,93	385,59	320,61	262,95
	7,5	110,27	187,78	488,42	711,49	716,08	714,18	710,23	688,60	619,98	546,87	473,59	403,49	338,95
	8,5	148,12	242,27	568,38	719,98	722,69	720,29	715,52	710,27	698,70	626,93	553,37	481,08	412,55
	9,5	189,11	298,04	639,45	726,89	729,60	726,70	721,19	714,98	709,27	696,81	624,52	552,07	481,71
	10,5	232,14	353,43	702,09	734,24	736,78	733,39	727,06	720,00	713,37	707,70	687,56	616,11	545,59

Table 3.2. The power matrix of the UGEN designed for deployment in Leixões is plotted. It is shown the power, in kW, in the shaft of the turbine for each sea state. In the vertical axis the wave significant height parameter is placed while in the horizontal axis the wave period parameter is shown.

The second step simply consists in multiplying the two matrices (scatter diagram x power matrix) and summing all the elements in the matrix to obtain the average power generation per hour [kW/h] for the specific location and device studied. The average power generation [kW] of the device in the specific location is obtained by multiplying by the number of hours of the year. The annual energy production [kWh/year] is obtained by multiplying the average power generation by the total number of hours in the year.

The result obtained is somewhat ideal, as it is considered that the UGEN operates without interruption over the entire year. In practise, this ideal generation has to be rectified due to the existence of non-operational periods (maintenance, failures, storms…). The availability factor is used to correct this ideal value to the real electricity generation. The availability factor is defined as the amount of the time that an electricity-generation plant is able to produce electricity over a certain period, divided by the amount of the time in the period. When no operational data is available, the available factor is assumed as a fixed percentage or is related to a more sophisticated estimate calculation based mostly on failure rates, duration and consequences of maintenance activities, maritime infrastructure requirements (port, vessels, equipment and personnel) and waiting time due to weather windows.

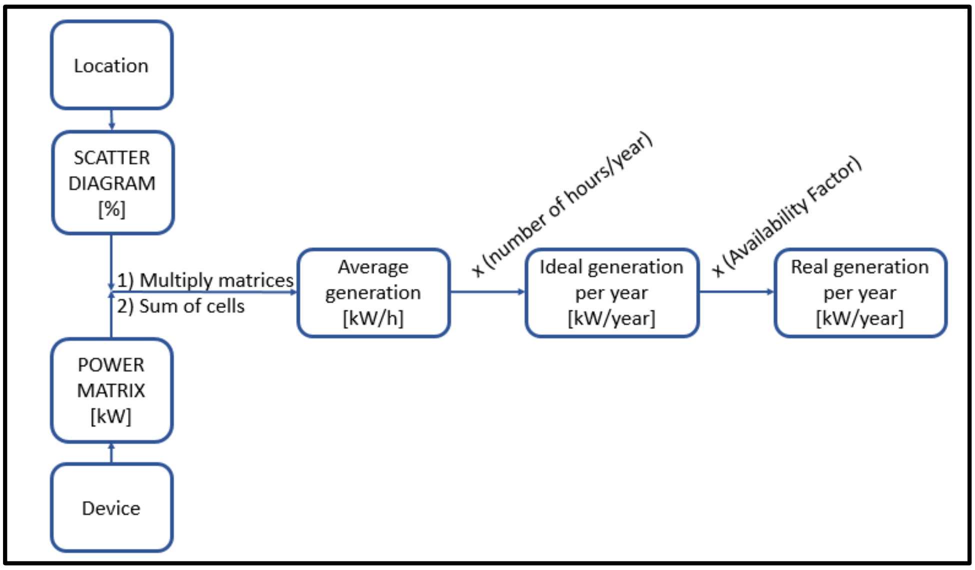


Figure 3.1. The diagram shows the steps and operations to calculate the average power generation per year.

There exist other important parameters which can be used to compute the AEP or can be derived from it. For instance, the capacity factor (CP) is defined as the amount of energy delivered during a year divided by the amount of energy that would have been generated if running at maximum power output the entire year, see equation (3.1).

$$CF = \frac{Annual\ Electricity}{8760h \cdot P_{rated}} \quad (3.1)$$

Another parameter which carries exactly the same information as the capacity factor is the full-load equivalent hours. It corresponds to the equivalent number of hours if running at maximum power output to produce the same annual electricity, see equation (3.2).

$$Equivalent\ hours = \frac{Annual\ Electricity}{P_{rated}} \quad (3.2)$$

In Figure 3.1 the steps and operations to calculate the electricity generation per year are shown.

3.2. CAPEX: cost models

The capital expenditures (CAPEX) or capital costs is the total cost needed to bring a project to a commercially operable status.

The components of CAPEX involved for marine renewables are [25]:

- Project management.
- Project development (surveys, lease, preliminary engineering, consulting, resource assessment, etc.).
- Component procurement (device, foundation/mooring systems, electrical connection systems, monitoring systems, etc.).
- Transport, assembly and installation (moorings, cables, devices, etc.).
- Test & commissioning, decommissioning and others.

The capital costs are often presented in unitary terms [€/kW]. Methods to estimate the CAPEX are essentially twofold [29]:

- “Bottom-up” process form individual components to get a direct cost for the item or items.
- References in the literature of CAPEX on a per kW or MW basis. The latter is typically more commonly found in the academic literature given the scarcity of project specific cost information in the public domain due to confidentiality issues.

To ensure that the cost quotations feeding the CAPEX are being compared on an equitable basis, it is important to take into account the inflation observed from the year of the source data [29].
A typical disaggregation of high level categories of CAPEX for a wave plant is: WEC device, PTO and support (50-60%), installation costs (15-20%), electrical connection (15%) and others.

In [2, 3] it can be found a spreadsheet-based capital costing model developed by Thorpe. The model defines four major cost centres for any wave power scheme: device structure, mechanical and electrical plant (M&E), electrical transmission, transportation and installation.

The scheme is described by three sets of parameters [27]:

- Project parameters: type, scale, location and time scale of the project.
- Independent parameters: location of the construction yard, area for deployment and point of connection to the domestic grid, as well as the water depth and sea bed condition at the deployment site.
- Dependent parameters: These can be deduced from the foregoing parameters by algorithms or defaults. One example of an algorithm is how the device type, total output and project duration would define the total number of devices, the number to be built each year, and hence the size of the construction facility. Typical defaults would be the type of M&E plant or the amount of concrete used in construction for each device type.

3.3. OPEX

Operational expenditure (OPEX) or operational costs are the expenses which are related to the operation and maintenance of a power plant during its useful life. The methods to calculate the OPEX are: €/MW per year, % of CAPEX per year (used when there is very little information available), €/MWh of electricity produced (not adequate for demonstration projects because the generation of electricity does not reflect a commercial power plant) and aggregation of all individual operations costs contributors (time consuming and require a large amount of data).

The components of OPEX can be divided in two groups, see [25]:

- Fixed: constant whether the device is operating or not. Examples are administrative costs, insurance, yearly rent/lease, planned maintenance and other contracts.
- Variable: depend on production or other variable factors. Examples are operation, unplanned maintenance & repair, spare parts.

There are two main types of maintenance tasks which are necessary to keep an ocean energy technology: scheduled maintenance and corrective or unscheduled maintenance. Scheduled maintenance is a planned process in which maintenance actions are carried out in accordance with an established work plan often based on the terms and conditions of the contracts with Original Equipment Manufacturers (OEMs). It also includes all servicing tasks and equipment certification processes. Scheduled maintenance is estimated on the basis of assumed device reliability and warranty and the average duration of a maintenance task, whilst unplanned maintenance can be related to the frequency of occurrence of extreme wave conditions at the project site. Unscheduled maintenance or repair is by definition unplanned, and consist of repairing elements and/or equipment back to a functional status.

A typical disaggregation of the OPEX for a wave farm is, [25]: Planned maintenance (29%), unplanned maintenance (28%), refit, understood as reconditions and repairs (24%), insurance (14%), monitoring (4%) and licenses (1%).

OPEX typically cover three main components of O&M costs [26]:

- Cost of spares: costs associated with spare parts to replace faulty equipment.
- Repair costs: in practice the faulty equipment replaced by the spare parts previously mentioned would be repaired and used as spares in the future.
- Operational costs: these are the costs associated with providing maintenance crews and vessels as well as any consumables to enable repairs to be carried out.

3.4. Discount rate

In finance, the discount rate can be seen as the interest rate used in discounted cash flow (DCF) analysis to determine the present value of the future cash flows [27]. The discount rate is widely used to know the value of a company today. Knowing the future earnings in the following periods the discounted cash flow is calculated using the discount rate in order to predict which the value of the company is nowadays.
The value of the discount rate can be related to two core concepts [27]:

- Time value of money. The inflation decreases the value of money with time.
- The projection of a project in the future always implies uncertainty and risk. This uncertainty attached to future payments or charges is also included in the discount rate.

A greater value of the discount rate implies more uncertainty while a lower value means less uncertainty and inflation. To determine a proper value of the discount rate is a complex process. To finance an offshore renewable energy project, the investment money usually comes from several sources (loans, investors, grants…) which have their own interest rate. The cost of capital can be represented by the weighted average of the interest rates of the different sources [25], see (3.3).

$$WACC = \sum_{n=1}^{N} int.rate_n \cdot \%inv._n \qquad (3.3)$$

$WACC$ [%]: Weighted average of the interest rate.

- $int.rate_n$ [%]: Interest rate of the investment n.
- $\%inv._n$ [%]: Percentage of the money invested in the investment n over the total money invested.

In essence, the discount rate is the rate of return that investors could expected to earn in an alternative investment of equivalent risk. So it depends on the investor's risk perception and willingness to invest. While for mature technologies (carbon, wind…) it is about 5-10% for new technologies (wave, tidal…) is approximately 12-18%.
Regarding the LCOE analysis the discount rate is used to readjust all costs (CAPEX and OPEX) and AEP involved during the life of the device to its present value.
The cost of electricity is one of the most commonly used techno-economic indicators to compare the commercial viability of a set of energy projects.

3.5. LCOE

The Levelised Cost Of Energy (LCOE) is defined as the average cost per unit of useful electrical energy produced by a electricity-generation plant during its lifetime [28], see equation (3.4).

The LCOE is an economic assessment of the average total cost to build, operate and decommission a power-generating device over its lifetime divided by the total energy output of the device over that lifetime. It is typically expressed in cents/kWh or €/MWh. The LCOE can also be regarded as the minimum cost at which electricity must be sold in order to break-even over the lifetime of the project.

The main factors involved in the LCOE computation are shown in Figure 3.2: CAPEX, OPEX and AEP [25].

$$LCOE = \frac{PV\ (Costs)}{PV(Electricity)} = \frac{\sum_{t=t_0}^{n} \frac{I_t + O\&M_t + F_t + D_t}{(1+r)^t}}{\sum_{t=t_0}^{n} \frac{AEP_t}{(1+r)^t}} \tag{3.4}$$

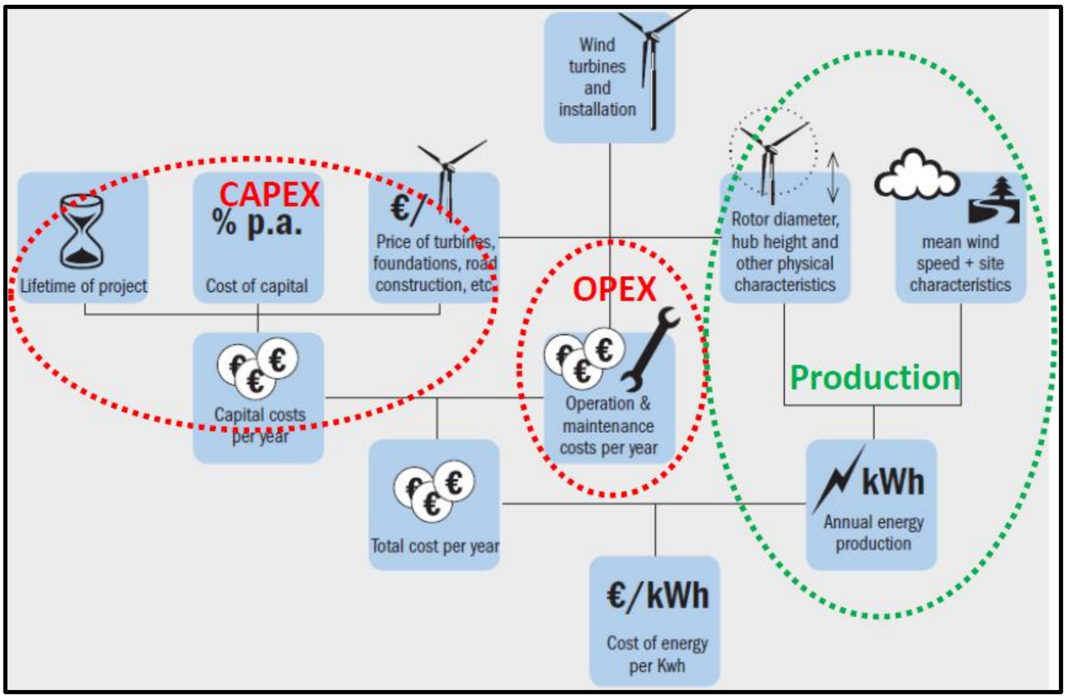


Figure 3.2. The components of the LOCE. On the left the CAPEX variables are shown, in the middle OPEX is shown while on the right the AEP is placed [25].

A typical disaggregation of the LCOE for a wave farm is, [25]: Device (43%), OPEX (30%), moorings and foundations (10%), installation (9%), grid connection (5%) and project development (3%).

Due to the apparent simplicity of an LCOE calculation, this economic metric has become a starting point for discussions of the economic viability of alternative energy production technologies. However, the following are a number of reasons why the results of an LCOE assessment should be interpreted with care:

- LCOE results are highly dependent on the discount rate used. There is no consensus as to what are the standard rates to use in offshore renewable energies.
- Single-point estimates of the costs of each technology are sensitive to the assumptions used.

- The method typically assumes that the project characteristics (such as capacity factor, or annual O&M costs) are constant throughout the lifetime of each facility, which might not reflect operational conditions.
- The costs included in the calculation sometimes differ across studies so users should be cognisant of the costs considered.
- The value of energy is assumed constant and this is to the detriment of systems that may be operated when the market value is higher.

3.6. WavEC techno-economic model

In this thesis, the WavEC techno-economic model has been used. The model has been developed internally with the aim of calculating and estimating the LCOE as well as other financial and risk indicators for different WEC systems.

The model is divided in the following modules: location, farm design, WEC design, CAPEX, OPEX, energy and LCOE. In each module, some input variables are required to define the characteristics or costs that the device is going to imply. The total sum of life cycle expenses associated with the power plant is estimated along with the total energy output predicted during the lifetime of the power plant.

Furthermore, the WavEC techno-economic model allows to introduce a specific range of variability for selected input parameters. This option reflects the uncertainty of some information when forecasting costs and energy production in the future. The use of learning rates at device or farm levels can also be implemented in the model.

As follows, the modules of the WavEC techno-economic model are briefly summarized, specifying the variables that define each module.

- Location: scatter diagram, site location & infrastructure, existing onshore connection, water depth and seabed conditions, see " 4.1.1. Location".
- Farm design: farm layout, offshore electrical configuration and mooring configuration, see "4.1.2. Farm design".
- WEC design: general description, power matrix, dimensions, material, ballast type and other structural costs, see "2.2. System description: main internal components" and "4.2.3. LCOE details".
- CAPEX: project development, WEC manufacturing, electrical connection, assembly installation & commissioning and monitoring & miscellaneous equipment, see "4.2.3. LCOE details".
- OPEX: management & administrative costs, annual monitoring & maintenance, onsite replacement & works, major replacement & works onshore and contingencies, see "4.2.3. LCOE details".
- Energy: mechanical losses and electrical PTO losses, see Annex D.1.
- LCOE: discount rate, construction period, project lifetime and decommissioning costs, see Annex D.2

4. Case study:

The following chapter presents the case study considered for this thesis.

4.1. Case description

The description is divided in three main modules: location, farm design and wave energy converter.

4.1.1. Location

The location where the devices are going to be deployed is a key-factor impacting many of the components of the LCOE: not only because of the available energy resource that can be harnessed but also because of the distance to the nearest port, the type of seabed (affecting notably the type of mooring and electrical system that can be installed), water depth, weather windows availability and extreme conditions.

In Table 4.1 and Figure 4.1, the generic information of the location where the 40 devices will be deployed is summarized:

Country	Region	Town	Coordinates of land connection
Portugal	North Portugal	Aguçadora	41º 26’ 30’’ N 8º 47’ 00’’ W

Table 4.1. General information of the location.

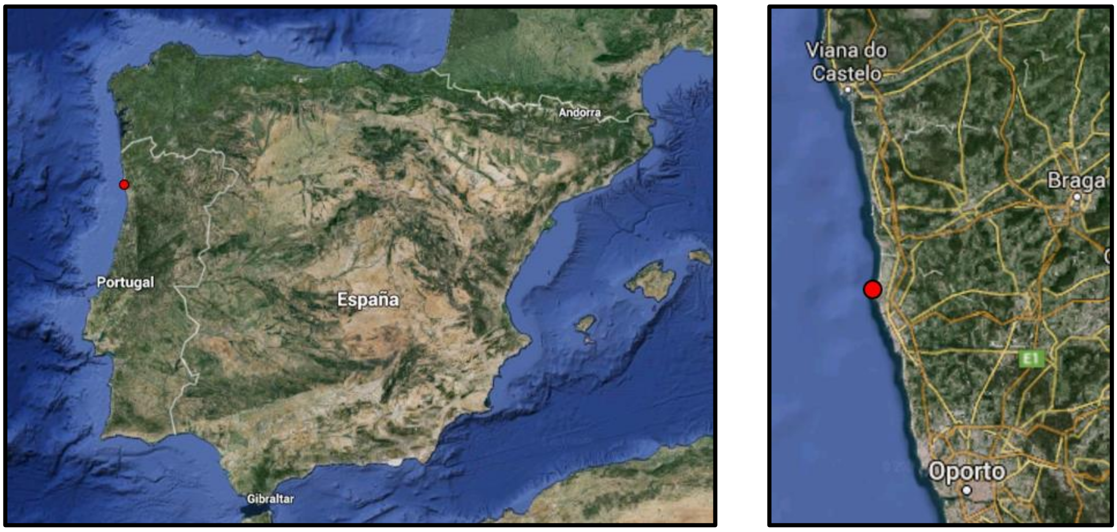


Figure 4.1. Aguçadora location shown. On the left, Aguçadora is shown inside the Iberian Peninsula. On the right, the near cities next to the location are shown, on the top Viana do Castelo, on the bottom Oporto and on the right Braga.

The location of Aguçadora has some advantages:

- Two full-scale wave energy projects have already been installed at this site (AWS and Pelamis).
- Availability of an on-site electrical infrastructure including a 4MW subsea cable, and 3 berths as well as an onshore substation
- Proximity of onshore infrastructure to support the logistics.

In Table 4.2 the characteristics of the location are shown.

Distance from nearest large port to site	Distance from nearest small O&M port to site	Distance from site to shore	Water depth	Type of seabed (site location)	Type of seabed (export cable)
Viana do Castelo	Póvoa de Varzim	4.5 km	40 m	Mud (0 %) Sand (90 %) Gravel (0 %) Rock (10%)	Mud (0 %) Sand (90 %) Gravel (0 %) Rock (10%)
26 km	11 km				

Table 4.2. Characteristics of the location. Distance, water depth and seabed.

Figure 4.2**¡Error! No se encuentra el origen de la referencia.** shows the three berth locations, the water depth and distance from site to shore at Aguçadora. For this initial study, the 40m deep berth site is considered suitable for the UGEN device.

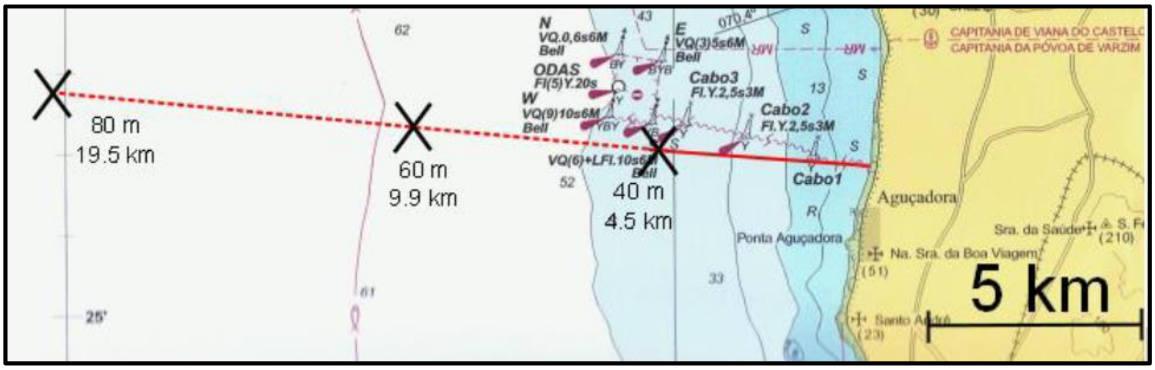


Figure 4.2. Possible locations of the farm in Aguçadora. On the bottom of the crosses the water depth and the distance from site to shore for each location are shown.

The scatter diagram used in the techno-economic is shown in Table 4.3. It corresponds to the location of Leixões (Port of Matosinhos), which is situated 30km south of Aguçadora. Obtaining the scatter diagram of Aguçadora has not been possible for the techno-economic study. The scatter diagram of Leixões is characterized for: water depth = 106m and a distance from site to shore = 6km. While the location of Aguçadora features: water depth = 40m and distance from site to shore = 4.5km. Further studies considering a scatter diagram of Aguçadora location will be required in order to refine the techno-economic analysis.

Frequency of ocurrence in %													
	Te [s]												
Hs [m]	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	16,5
0,5	0,07	2,41	2,21	0,33	0,01	0	0	0	0	0	0	0	0
1,5	0,03	6,26	17,18	13,02	7,42	2,67	0,39	0,13	0	0	0	0	0
2,5	0	0,23	3,16	5,78	7,1	6,3	3,65	1,12	0,18	0,01	0	0	0
3,5	0	0	0,03	1,17	2,79	3,2	2,47	1,22	0,39	0,11	0	0	0
4,5	0	0	0	0,01	0,64	1,43	1,45	1,06	0,51	0,18	0,02	0	0
5,5	0	0	0	0	0	0,36	0,83	0,61	0,33	0,07	0,03	0	0
6,5	0	0	0	0	0	0	0,17	0,34	0,18	0,06	0,05	0	0
7,5	0	0	0	0	0	0	0,03	0,07	0,13	0,05	0,02	0	0
8,5	0	0	0	0	0	0	0	0,01	0,05	0,09	0,03	0	0
9,5	0	0	0	0	0	0	0	0	0,03	0,05	0	0,01	0,01
10,5	0	0	0	0	0	0	0	0	0	0,01	0,01	0	0

Table 4.3. Scatter diagram for the location of Leixões.

4.1.2. Farm design

The farm design primarily concerns the number and the spatial distribution of devices. The major factors that have been considered to design the farm are the non-disturbance distance between devices while trying to minimize the costs associated to the electrical network configuration, the mooring system and the O&M considerations.

The farm will be composed of 40 UGENs. Since the rated power of a single UGEN unit is 0.5 MW, the final rated power capacity of the farm will be of 20 MW.

Farm layout

The array layout can be seen in Figure 4.3.

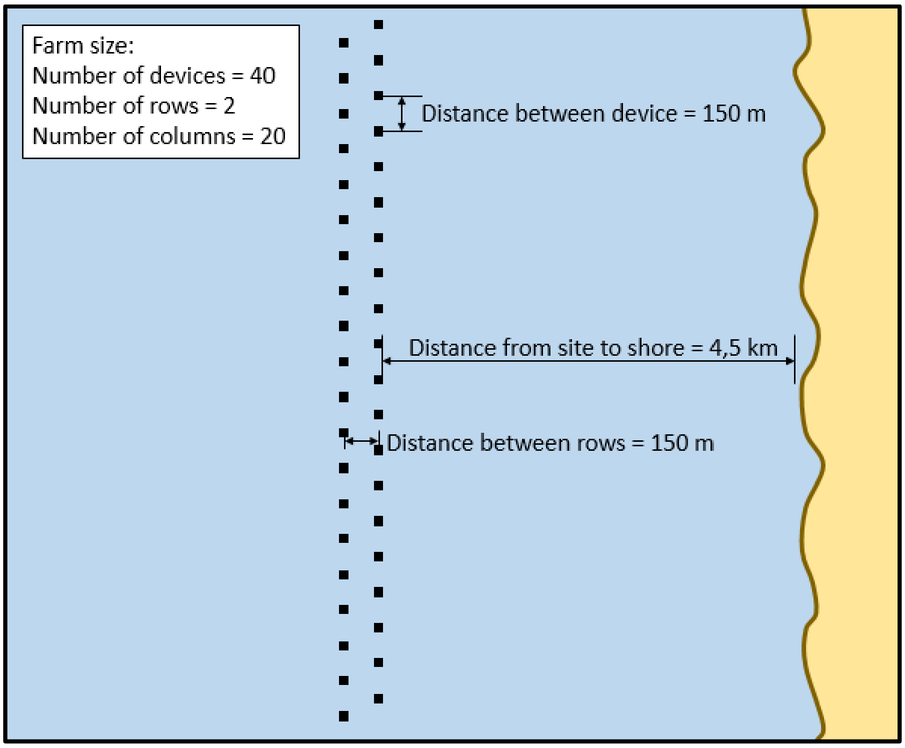


Figure 4.3. Array layout.

As a first approach, the array layout (i.e spatial positioning of the devices in the farm) has been determined to reduce hydrodynamic interferences while allowing sufficient inter-distances to accommodate the mooring footprint. It should be noted that no considerations for shared mooring lines or anchoring points have been made. When reaching a mature stage of project development, further studies and simulations will be carried out in order to maximize the power production and minimize the costs due to length of cables, moorings and common maintenance and therefore optimizing the array layout.

The distance between devices has been calculated assuming the mooring components and dimensions defined on a primary simulation for the moorings system for a water depth of 80m. The simulation has been performed by a mooring expert in WavEC using the software OrcaFlex. As shown in Figure 4.4, the simulation has calculated a horizontal distance between each anchor and the UGEN at an equilibrium position of 120 m.

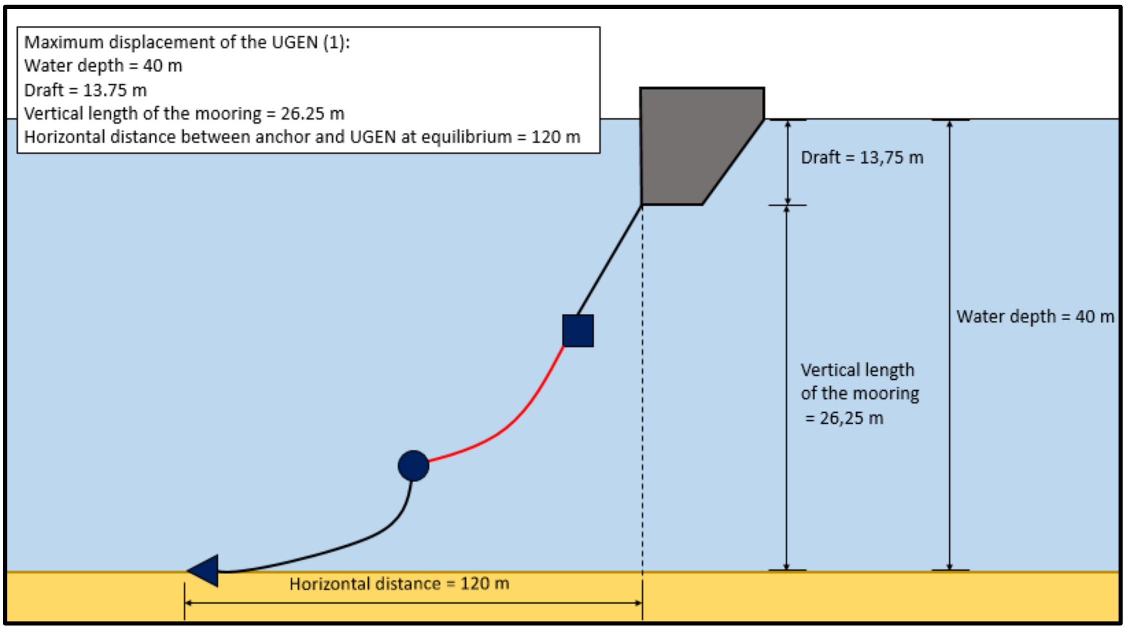


Figure 4.4. Horizontal distance between anchor and UGEN at equilibrium.

Although the mooring configuration of the UGEN device will be described below, the total length of the mooring line, 153m, is already stated to estimate the distance between devices. Indeed, the maximum displacement of the device will occur when the mooring line is tight, which means a total distance between anchor and UGEN of 153 m. As can be seen in Figure 4.5, the maximum horizontal distance between an anchor and its device is 148.60 m in the fully stretched situation. Therefore, it can be noted that from the undisturbed position to the fully stretched position, the maximum horizontal displacement is 28.6 m. Based on these values and in accordance with other practical limitations (e.g vessel route, limited hydrodynamic interferences and cable length), the distance between devices has been defined as 150 m to mitigate the risk of collision, assuming a safety factor of 5 after consulting the mooring expert of WavEC.

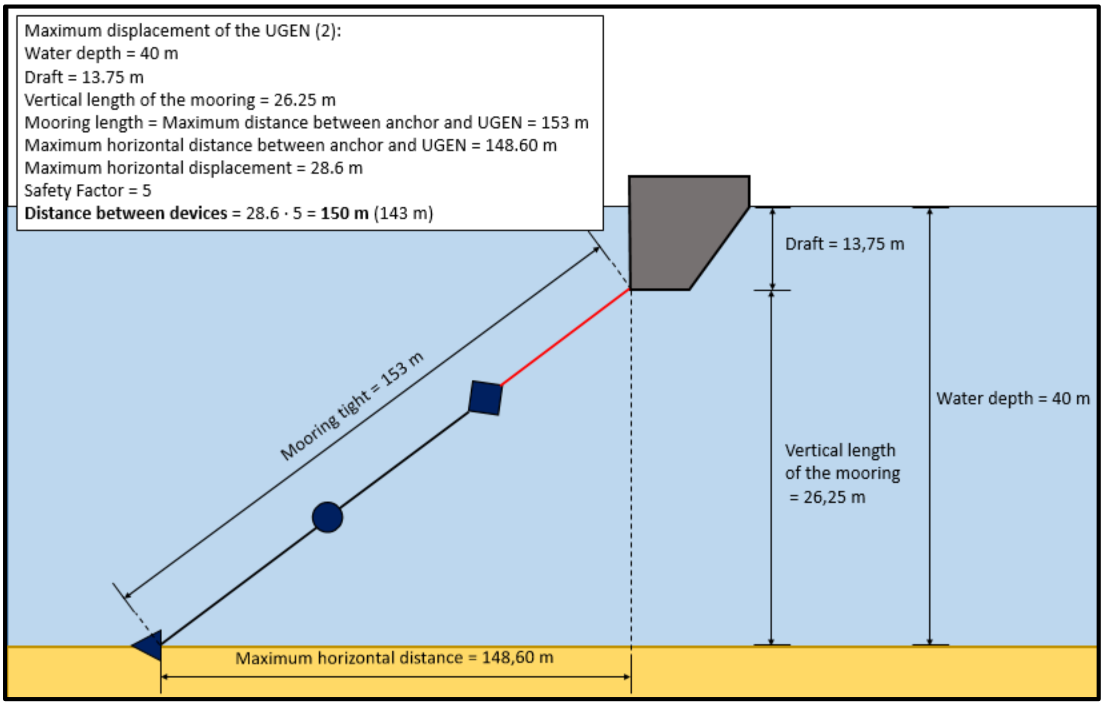


Figure 4.5. Maximum displacement of the UGEN.

Offshore electrical configuration

The electrical configuration has been designed following the more common structure for offshore electrical generation farms, such as wind farms or other wave farms.

Typical values for offshore renewable energy farms are 11 kV or 33 kV [30]. Usually, the voltage level for wind farms is 33 kV [30]. The voltage level is primarily determined with the objective to reduce high currents, losses and reactive power during the electrical transportation from farm to shore. In order to simplify the electrical connection equipment, and avoid the need for an offshore substation to rise the voltage, the voltage level has been assumed to be the same for the entire farm, from each device until the onshore substation. In this setting, the export cable power transmission rating was calculated to 20 MVA. The equation (4.1) calculates the circulating current intensity in the export cable [30]:

$$I = \frac{P}{\sqrt{3} \cdot U \cdot cos\phi} = \frac{20 \cdot 10^6 \, W}{\sqrt{3} \cdot 33 \cdot 10^3 \, V \cdot 0{,}96} = 364{,}5 \, A \tag{4.1}$$

- P = 20 MW
- $cos\phi$ = 0,96
- U = 33 kV

The current is acceptable, according to the three main conditions for voltage selection (heating of the conductor, voltage drop and short-circuit current) [30]. In practice, the total time at which a WEC device is producing at maximum rated power is relatively low due to the significant time variability of the wave conditions (from sea-state to sea-state and from wave-to-wave).

In this electrical configuration, the UGEN farm considered does not need an offshore substation in order to step-up the voltage [30]. The typical situation under which it is not required to install an offshore substation in the electrical configuration are:

- Farm total power rating less than 100 MW; here we have 20 MW.
- Distance from site to shore not exceeding 15 km. The distance to shore in our study was measured at 4.5 km.

A top view and a vertical cross-sectional view of the electrical layout configuration is shown in Figure 4.6 and Figure 4.7 respectively. The 40 devices form clusters of 8 units connected to a junction box, for each device, a sequence composed of an umbilical cable, a dry-mate connector and a dynamic cable. The 5 junction boxes are connected to the main collection hub which combines the 5 inter-array cables as input into a single static export cable landing to shore.

The electrical configuration has been inspired from the project wave hub [31], and the configuration presented on reference [30]. See in the Annex E.1 the wave hub project, composed by 4 umbilical cables, 4 dry mate connectors and 4 static cables, which are connected to the wave hub and the export cable. The configuration proposed in [30], see in Annex E.2 reduces as much as possible the length of the umbilical cable in order to avoid the forces and the consequently stress suffered in this cable. In order to reduce the length, the dry mate connector and dynamic cable are placed on the sea-bottom although not fixed to the sea bed.

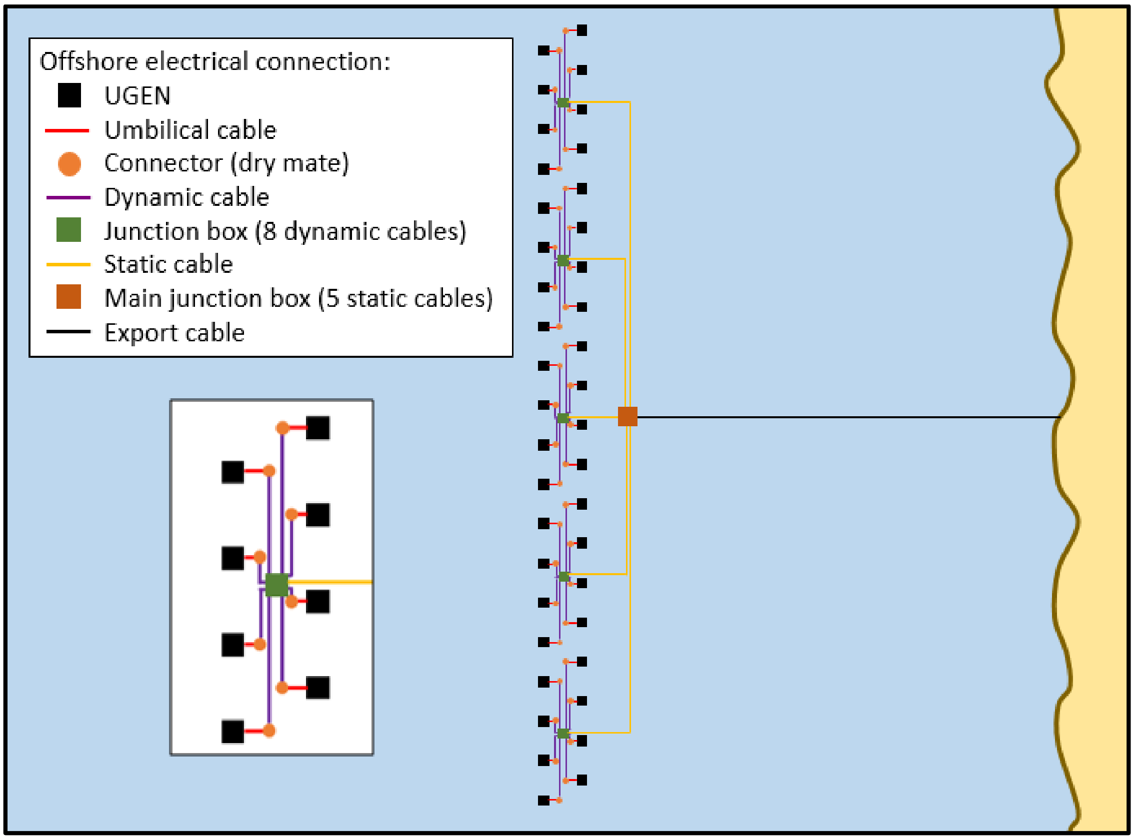


Figure 4.6. Electrical layout configuration, top view.

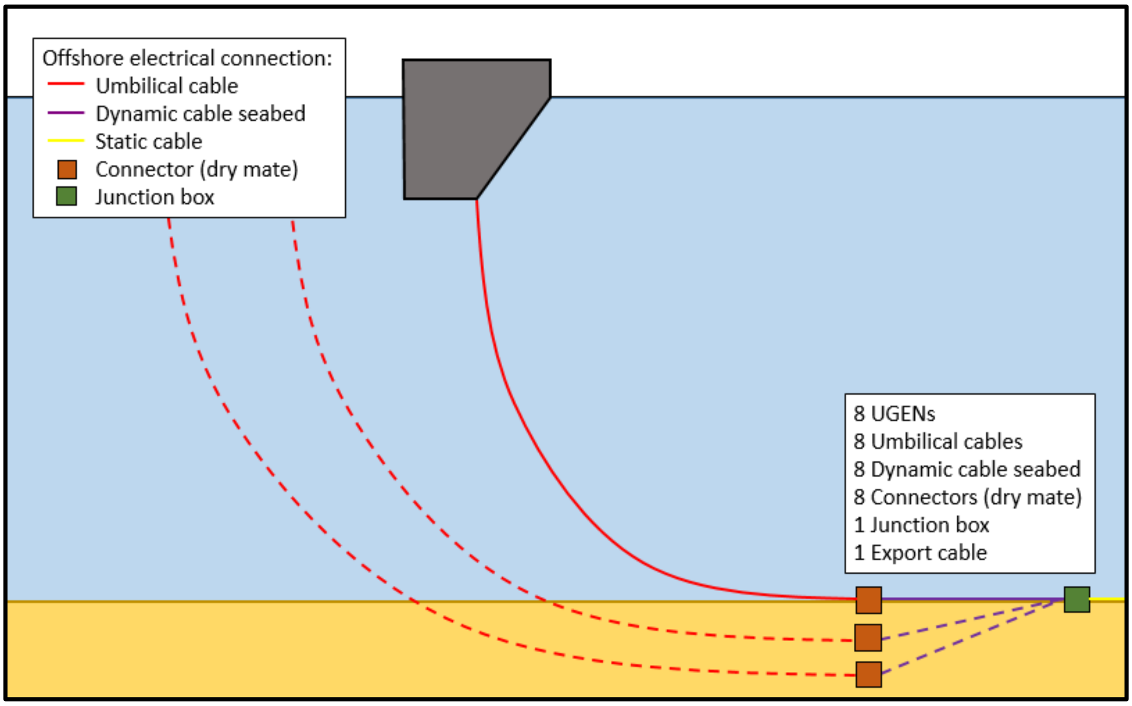


Figure 4.7. Electrical layout configuration, lateral view.

Mooring configuration

The components and dimensions of the mooring system for the UGEN device were firstly designed using a simple model in the software OrcaFlex assuming 80m water depth and 2 mooring lines per device. As the deployment site considered in the present study has 40m water depth, further studies will be required in order to optimize the dimensions of the mooring system. However, the mooring components specifications given by the OrcaFlex model for 80m water depth will be conservatively applied to the techno-economic analysis reported herein while assuming 3 lines per device (which is recommended given the directionality of the waves and the shape of the UGEN). A sensitivity analysis of the mooring length and drag embedment anchor will be carried out to understand the impact of this parameter on the LCOE. The UGEN device uses a conventional catenary mooring configuration for floating WEC as presented in Figure 4.8.

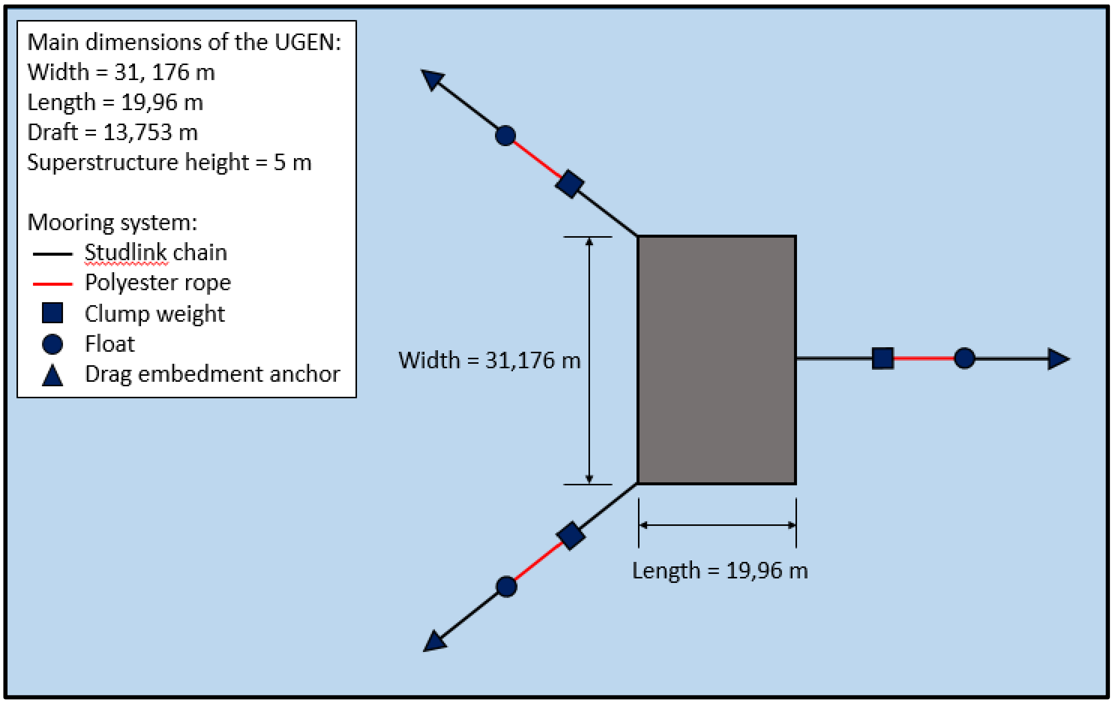


Figure 4.8. Mooring configuration. 3 mooring lines/device, top view.

As previously mentioned, the main specifications of the mooring system components were determined using the software OrcaFlex with the characteristics depicted in Table 4.4.

	Description	Quantity (per line)	Total weight
Drag embedment anchor	Weight in air = 9.07 tonnes	1	9,070 kg
Studlink chain	Bar diameter: 68 mm Weight in air: 101 kg/m SWL: 2450 kN MBL: 3495 kN	115 m	11,615 kg
Polyester rope	Diameter: 140 mm Weight in air: 15 kg/m MBL: 3341 kN	38 m	570 kg
Shackle	MBL > 3500 kN MBL = 245,25 kN	6	660 kg

Float	Weight in air: 14.5 kg Volume: 0.108 m^3	1	14.15 kg

Table 4.4. Mooring components and dimensions for each mooring line.

In Figure 4.9, a cross-sectional vertical view of the mooring system is shown.

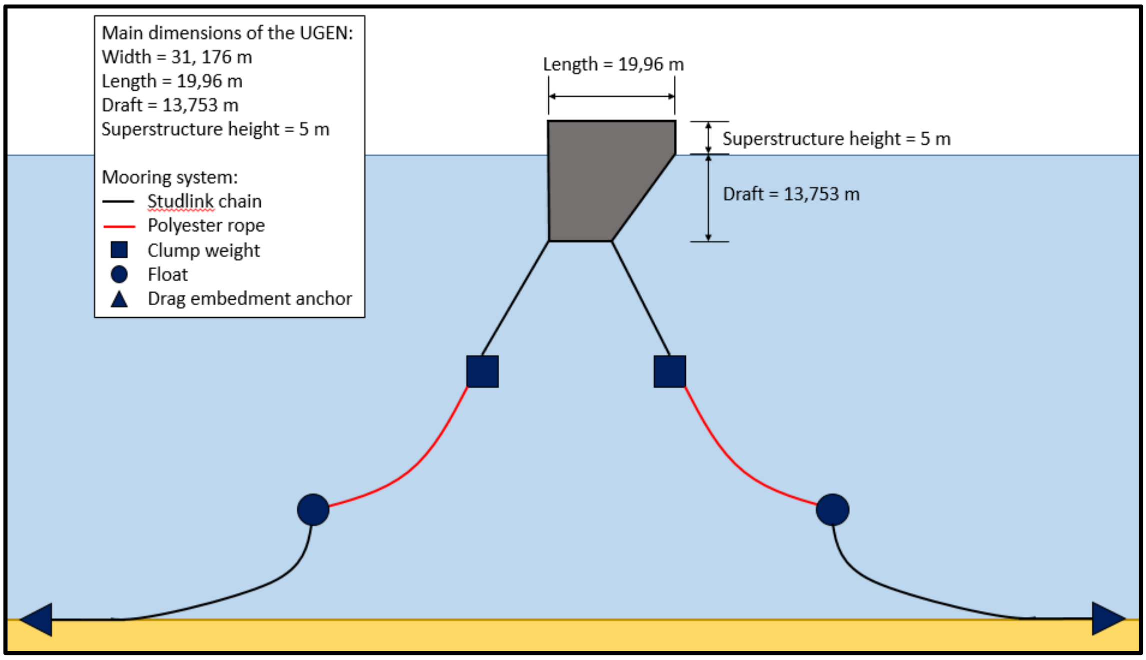


Figure 4.9. Mooring configuration. 3 mooring lines/device, lateral view.

4.2. LCOE for the reference case

4.2.1. LCOE overview

The LCOE value for the 20 MW farm composed by 40 UGENs was found to be 59.01 c€/kWh =590.1 €/MWh. This value corresponds to the "reference case" in this study which makes uses of the best estimates and central values for the expected ranges of the uncertain input parameters.

Table 4.5 summarizes the values and percentages of the CAPEX, OPEX and decommission costs breakdown. In Figure 4.10 the desegregation in percentages of the LCOE is shown in a graph.

	Value	Units	% LOCE
CAPEX. Project development	150	€/kW	2.00
CAPEX. WEC Manufacturing	4,388	€/kW	58.42
CAPEX. Electrical Connection Equipment	496	€/kW	6.60
CAPEX. Assembly, Installation & Commissioning	899	€/kW	11.96
CAPEX. Monitoring & Miscellaneous equipment	13	€/kW	0.18
CAPEX.	5,946	€/kW	79.16
OPEX	208.10	€/kW/year	20.33
Decommission costs	297.29	€/kW	0.51

Table 4.5. LCOE values and percentage desegregated in CAPEX components, OPEX and decommission costs.

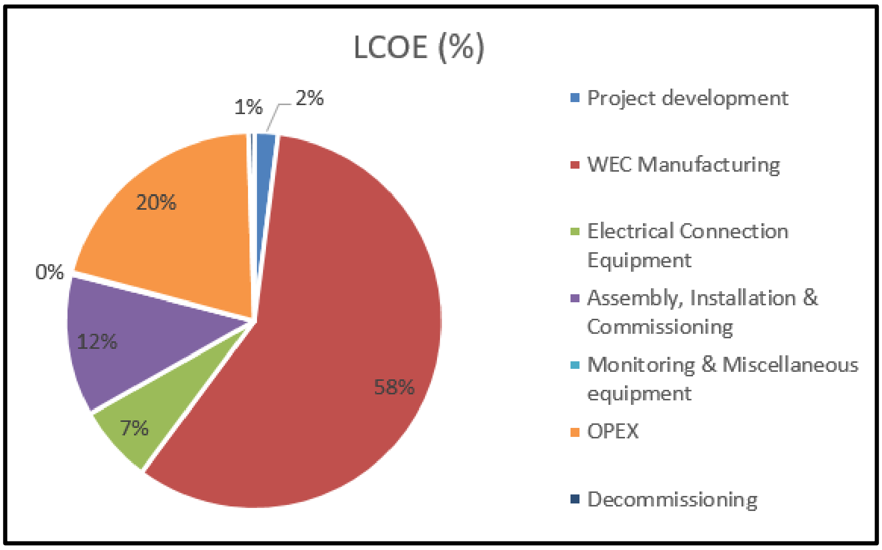


Figure 4.10. Graph showing the LCOE percentage desegregated in CAPEX components, OPEX and decommission costs.

4.2.2. LCOE comparison

To give some hindsight and context of the LCOE value calculated for the UGEN, comparative values for other offshore renewables energies were researched in the literature [25].

	LCOE [€/MWh]	CAPEX [€/kW]	OPEX [€/kW/year]
UGEN	590.1	5,946	208.10
Offshore wind	100 – 250	3,000 – 3,500	80 – 120
Tidal	150 – 300	3,000 – 5,000	130 – 210
Wave (pre-commercial stage)	200 – 700	5,000 – 7,000	300 - 450
Wave (commercial stage)	100 – 300	3,000 – 4,500	200 – 300

Table 4.6. Comparison of the LCOE, CAPEX and OPEX between offshore renewable energies.

In Table 4.6, it can be noticed that the device presents a reasonable cost distribution and should be considered as a pre-commercial wave power plant.

Concerning the CAPEX, Table 4.7 depicts the disaggregation of the UGEN power plant capital costs while comparing it with reference values found for a wave plant [25].

	Reference values [%]	UGEN power plant [%]	
WEC	50 – 60	Structure 32.21	58.42
		PTO 19.60	
		Moorings 4.78	
		Others 1.83	
Installation cost	15 – 20	11.96	
Electrical connection	15	6.60	
Project development	-	2.00	
Monitoring & miscellaneous equipment	-	0.18	

Table 4.7. Comparison of CAPEX disaggregation between reference values and UGEN power plant values.

The percentage of the WEC is slightly high but still in the defined interval, while the installation cost and the electrical connection are lower than the reference values which may be explained by the low distance from site to shore (4.5 km), reducing the costs associated to the export cable and its installation.

4.2.3. LCOE details

The costs involved in the project are dived in CAPEX, OPEX and decommission costs.

CAPEX calculation

The CAPEX have been divided in five main categories:

- Project development, see
- Figure 4.11.
- WEC manufacturing, see Figure 4.12.
- Electrical connection equipment, see Figure 4.13
- Assembly, installation & commissioning, see Figure 4.14.
- Monitoring & miscellaneous equipment, see Figure 4.15.

PROJECT DEVELOPMENT	Cost [k€]
Project Management	104
Surveys	510
Engineering consulting fees	176
Legal & financial costs	2,213
TOTAL PROJECT DEVELOPMENT	3,003

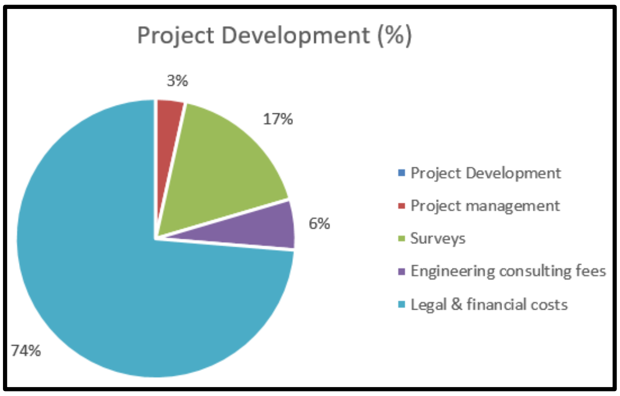


Figure 4.11. Project development costs and graph desegregation.

WEC MANUFACTURING	Cost [k€]
Structure	48,380
PTO system	29,440
Ancillary system	2,146
Main structure assembly & installation	608
Station keeping system	7,180
TOTAL WEC MANUFACTURING	87,753

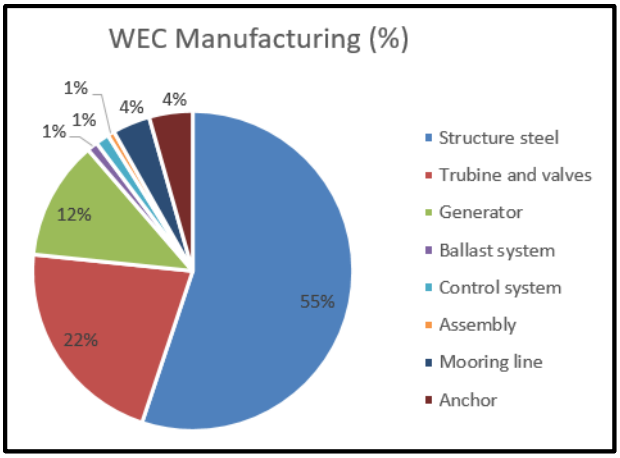


Figure 4.12. WEC manufacturing costs and graph desegregation.

ELECTRICAL CONNECTION EQUIPMENT	Cost [k€]
Umbilical	1,836
Connectors	6,000
Dynamic cable	91
Junction box	750
Static cable	117
Main junction box	250
Export cable	878
TOTAL ELECTRICAL CONNECTION EQUIPMENT	9,922

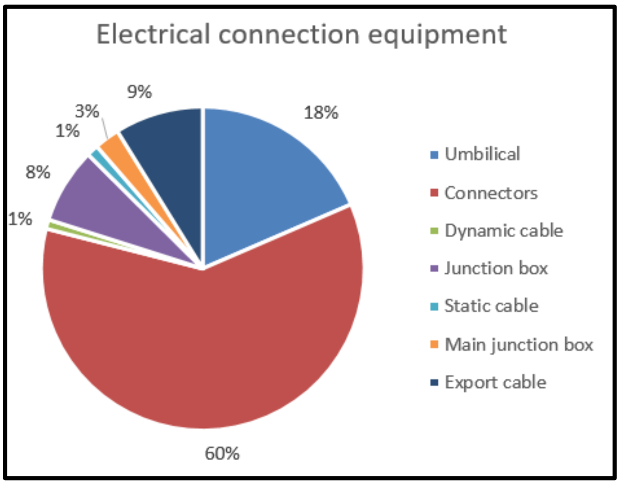


Figure 4.13. Electrical connection equipment costs and graph desegregation.

ASSEMBLY, INSTALLATION & COMMISSIONING	Cost [k€]
Installation of mooring system	2,247
Installation of electrical connection	13,982
Installation of main structure	1,507
Commissioning & testing	57
TOTAL ASSEMBLY, INSTALLATION & COMMISSIONING	17,973

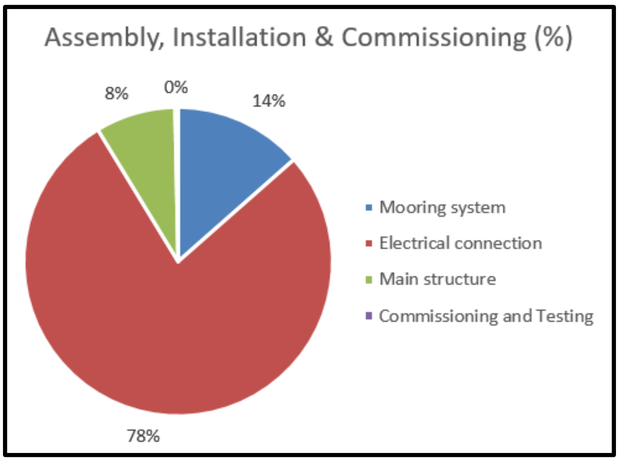


Figure 4.14. Assembly, installation & commissioning costs and desegregation.

MONITORING & MISCELLANEOUS EQUIPMENT	Cost [k€]
Monitoring	40
Support services infrastructure	226
TOTAL MONIOTIRNG & MISCELLANEOUS EQUIPMENT	266

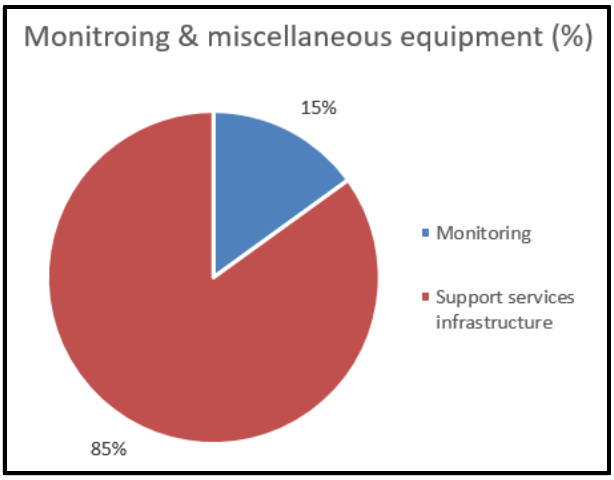


Figure 4.15. Monitoring & miscellaneous equipment costs and desegregation.

See Annex F.1, F.2, F.3, F.4 and F.5 for a more detailed desegregation of the CAPEX.

In Table 4.8 a summary of the CAPEX divided in the main groups is plotted, while in Figure 4.16 the percentage desegregation is shown in a graph.

Component	Cost of the farm [k€]	Cost of the farm per power unit [€/kW]	% LCOE
Project development	3,003	150	2.00 %
WEC manufacturing	87,753	4,388	58.42 %
Electrical connection equipment	9,922	496	6.60 %
Assembly, installation & commissioning	17,973	899	11.96 %
Monitoring & miscellaneous equipment	266	13	0.18 %
TOTAL CAPEX	**118,917**	**5,946**	**79.16 %**

Table 4.8. CAPEX desegregation.

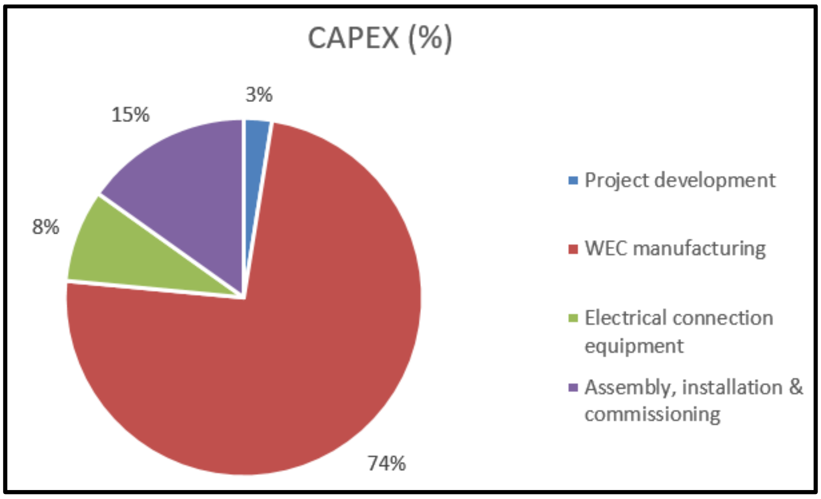


Figure 4.16. Graph of the CAPEX desegregation in percentages.

Assuming a construction period of 3 years and a discount rate of 10% the investment costs increase from 5,946 €/kW to 6,899 €/kW. Investment costs refer to the capital required to bring the project to an operable status. This as a result of the devaluation of money during the construction period. The investment costs contribution to the LCOE is 47.71 c€/kWh.

Justification of the underlying values and assumptions

Wave energy is still an emerging sector with very few WECs installed in the world. This early stage status means a limited availability of public information associated with costs, procedures, manufacturing, etc. In order to proceed with the techno-economic analysis some values have been assumed or extracted from offshore wind projects. Although it is an early technology and there is limited experience, wind offshore has been more widely studied nowadays.

Project development.

Wave hub being a grid-connected wave power test site with the same total power capacity than the UGEN farm considered, 20MW, is considered suitable to exploit the available data from this project in the techno-economic analysis of the UGEN farm. However, the wave hub is located in the United Kingdom. The difference in the cost of living between UK and Portugal introduces a difference on the cost of the project development [47, 48]. To-date, no similar wave energy project with the characteristics of the UGEN farm envisioned in this study has been developed in Portugal, which is why data from other countries and other related sectors have to be sought.

Turbine and valves & generator.

Both the valves and electrical generator costs were estimated following the method proposed in reference [34] which can be read from equation (4.2).

$$Cmech\ (D) = Cmech, o \left(\frac{D^3}{Do^3}\right)^{0,6} [k€] \tag{4.2}$$

- $Cmech, o$: Cost of the turbine of the Pico plant in 2002, 330 k€.
- Do: Diameter of the turbine of the Pico plant 2,3m.
- $Cmech$: Cost of the turbine of the UGEN in 2002.
- D: Diameter of the turbine of the UGEN, 2.75m

The mechanical equipment, denoted C_{mech}, comprises the air turbine, the valve or valves and the ducting system. It is assumed that the cost depends on the turbine size (represented by the rotor diameter *D*) according to some empirical algorithms. For a power rate of 0.5 MW the reference proposes a suitable turbine diameter 2.75m. The actualized cost to the current year, considering the interest rate from 2002 until 2016 in Portugal (3.6 %) [41], is 472 k€.

The electrical equipment comprises the generator, the power electronics and conventional equipment (transformer, circuit breakers, switch boards, cabling, etc.), whose total cost is taken as a function of the rated power of the plant [34]. The cost is defined by the equation (4.3).

$$Celect = 3,3\ Prated^{0,7}\ [k€] \tag{4.3}$$

- $Prated = 500\ kW$ [year 2003]

The actualized cost, considering the interest rate of 2003 until 2016 in Portugal (3.23%) [41], is 264 k€.

Installation operation time.

The time required for each operation during the installation of the farm is detailed in Table 4.9.

Operation	Time [days/device]	Comments/assumptions
Installation of mooring system		
Offshore work - Anchor handling vessel	0.97	8 hours/device installation + distance to deployment point at charged speed (6 knots) + distance to port at transit speed (12 knots)
Dock work - Anchor handling vessel	0.17	2 hours/device

Technicians – Preparation in the dock	0.33	4 hours/device.
Rest of operations	1.13	Sum of offshore work and dock work of the anchor handling vessel
Installation of electrical connection		
Dynamic cables	0.83	10 hours/device to install umbilical and dynamic cable
Static cables	1	1 day/cable. The export cable and the 5 static cables.
Connection points	1	1 day/connection point. The main junction box and the 5 junction boxes.
Installation of main structure		
Offshore work - Tug vessel	0.35	3 hours/device installation + distance to deployment point at towing speed (2.5 knots) + distance to port at transit speed (10 knots)
Dock work – Tug vessel	0.33	4 hours/device.
Rest of operations	0.68	Sum of offshore work and dock work of the tug vessel.

Table 4.9. Installation operation time.

Due to the lack of operational experience, the installation process has made use of default values based on guidance provided by an expert of WavEC Offshore Renewables of marine operations for the operations that couldn't be estimated or calculated.

Weather downtime.

The weather downtime has been calculated following the approach described in [35] which determines the available days for the installation process using a statistical equation that depends on the average Hs of the location. The average H_s of the location was found to be 2.28 m for the scatter diagram of Leixões. It has been assumed that the installation of the UGEN devices will occur during summer season because the average accessibility to the site is higher in terms of operational limit conditions related to Hs.

Equation (4.4) below calculates the number of accessible days (maximum threshold of 1.5-2m) in a month during the summer season as a function of the average H_s. For this study, it was assumed that a value of 1.5m is representative of the type of towing boat suitable to operate the installation of the UGEN device.

$$Number\ of\ accessible\ days = -27.78 \cdot \ln(Significant\ wave\ height\ average) + 38.823 \quad (4.4)$$

Under these conditions (average Hs at Leixões of 2.28m), it was found that an average of 16 days per month are available for marine operations, using equation (4.4). This corresponds to 48% of days where the installation of the device cannot be performed. The cost associated with the weather downtime has been calculated as the multiplication of the percentage of inaccessible days, and the costs of the equipment required in each operation, such as cranes, vessels, technicians on the dock... It should be noted that this method is simplistic and more sophisticated weather window modelling approaches exist, including those developed under the DTOcean project by WavEC.

Seabed type.

The seabed type is a critical factor of the electrical connection installation and in the design choice of the anchoring system. The LCOE model uses a weighted mean coefficient depending on the sea bottom type to adjust the cost of the electrical connection installation. The coefficient is directly applied to the price of installing the mooring system and the electrical connection, which are the ones affected by the different seabed types. The correcting factor is based upon the European expert group workshop in 2012. Although this approach accounts for the possibility of requiring to work with different seabed conditions, thus making the analysis more reliable, it remains the case that this model for analysis lacks precision when considering the location of deployment.

OPEX calculation

Since the UGEN wave energy farm project is at an early stage of development, there remain strong uncertainties with respect to the final design and components. Consequently, it is very difficult to obtain failure rates of the components from the suppliers in order to proceed with a statistical analysis. The frequency of failure of the components together with the failure modes determine the type of maintenance operations and frequency that, in turn, can be used to build a detailed O&M model estimating both the OPEX and the farm downtime. In our study and for simplicity, OPEX has been computed as a direct percentage of the CAPEX previously determined. See Table 4.10.

	Reference	Price	Cost [€/kW/year]	Cost [c€/kWh]	% LCOE
OPEX	[25, 32, 33]	3.5 % of CAPEX	208.10	12.00	20.33 %

Table 4.10. OPEX costs estimation [25, 32, 33].

Decommission costs calculation

The decommissioning costs are often considered as a percentage of the CAPEX in techno-economic studies related to offshore renewable energies, since very few offshore power plant have been dismantled to-date. Furthermore, decommissioning costs will be highly project specific depending on factors such as the local regulatory framework. In [38], a value of 5% of the total CAPEX was considered, and appears to be used in many other studies which is why it has also been taken as reference for the UGEN wave energy farm analysis as shown in Table 4.11.

	Reference	Price	Cost [€/kW/year]	Cost [c€/kWh]	% LCOE
Decommission	[38]	5 % of CAPEX	297.29	0.30	0.51 %

Table 4.11. Decommission costs estimation [33].

4.2.4. Comparison between MatLab subroutine and WavEC techno-economic model

The initial calculation of the LCOE for the UGEN was found to be 25.6 c€/kWh. However, the analysis was performed with a low level of details. The LCOE was calculated using a MatLab subroutine, which was used to conduct the optimization studies for the UGEN. The following comparison between both models (MatLab subroutine and WavEC techno-economic model) will allow to enhance the MatLab subroutine in order to improve further optimizations.

- The WEC manufacturing has given a simiar cost as a result of being computed in the same way.

- The OPEX has been set as a percentage of the CAPEX on both models. While MatLab subroutine accounts a 10% of the CAPEX, the WavEC techno-economic model just a 3.5% of the CAPEX has been invoiced [25, 32, 33].
- The MatLab subroutine accounts 2,500 k€ in concept of others. While in WavEC techno-economic model the total sum (project development, electrical connection equipment, installation & commissioning and monitoring & miscellaneous equipment) adds up to 31,164 k€.
- A decommission cost of 5% of CAPEX is included in in the WavEC techno-economic model but not in the MatLab subroutine.

The major difference between both models are the costs involved in the project development, electrical connection equipment, installation & commissioning and monitoring & miscellaneous equipment, which are under estimated in the MatLab subroutine.

5. Identification of the major costs and opportunities for cost reductions

Following the estimation of a reference base value of the UGEN wave energy farm, this section aims at clearing the way of the major cost reduction paths.

The already presented Figure 4.10, shows the LCOE disaggregation from which the three major costs are the WEC manufacturing (58%), the OPEX (20%) and the assembly, installation & commissioning (12%).

WEC manufacturing

Figure 5.1 indicates that the structure steel represents over half of the total WEC manufacturing CAPEX followed by two other significant cost drivers, namely the turbine and valves and the generator.

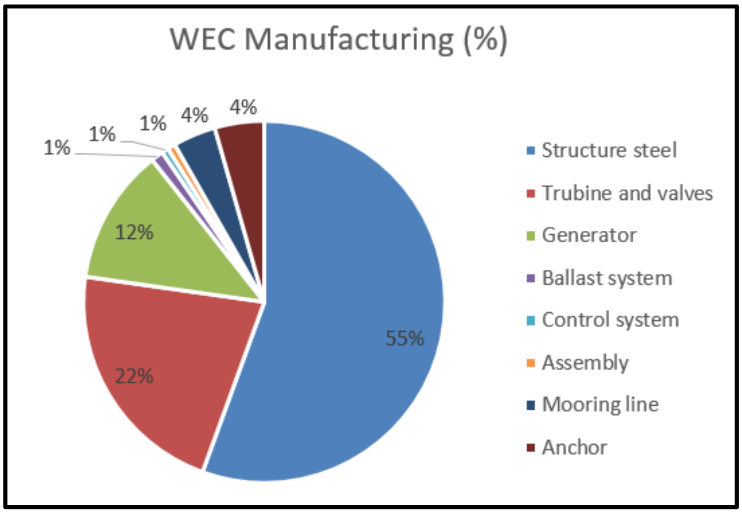


Figure 5.1. Graph of the WEC manufacturing disaggregation in percentages.

Structure steel.

The structure of steel cost has been evaluated based on the total mass of steel of the device and an approximate estimation of the cost of manufactured steel for shipbuilding applications. The cost of steel has been determined by a quotation of a Portuguese shipyard, 2,950 €/tonne [36] and corroborated with other quotations and references such as in [39] where it is indicated 3,000 €/tonne. However, the exact mass of the device will become more accurate when the final scantling of the device will be available and presented to the shipyard. In addition, the price of steel is a volatile cost subject to the variations of the value market [40]. For these reasons, a sensitivity analysis has been performed, varying the cost per tonne to quantify the effect on the LCOE.

Turbine and valves & generator.

The empirical algorithm proposed in [34] has been used and corroborated by confidential quotes obtained by WavEC for the Pico wave energy plant. Given the underlying uncertainty behind the empirical algorithm and the outdated quotations obtained for the Wells turbine, valves and generator, a sensitivity analysis will also be conducted on these components.

Mooring system and anchor.

Although representing "only" 2,21% of the LCOE, the cost associated with the mooring system may be overestimated as it was originally designed for 80 m water depth instead of 40m. Consequently, a sensitivity analysis has been performed looking only at lower of the reference case.

Distance between devices.

Since the distance between devices also rely on the 80m water depth mooring design, this parameter will be the object of a sensitivity analysis in the same fashion as the mooring system.

Assembly, installation & commissioning.

Four different tasks were identified: installation of mooring system, installation of electrical connection, installation of main structure and commissioning and testing.

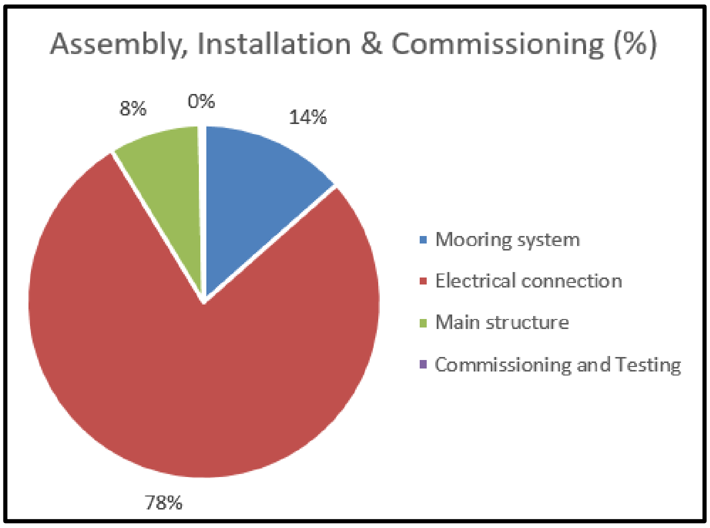


Figure 5.2. Graph of the assembly, installation & commissioning disaggregation in percentages.

In Figure 5.2 the percentages of the assembly, installation & commissioning are shown. It can be seen that the major cost is due to the electrical connection installation (79%), followed by the mooring system (14%) and the main structure (8%). Although the higher costs are the electrical connection and the mooring system installation, no cost reduction opportunity has been projected for the moment for these operations. Nevertheless, the main structure installation has presented different possible solutions considering the high weight of the device (410 tonnes). The transportation from dock to sea is a key factor, where cost reduction can be achieved. The project team has suggested to accomplish the operation by using a crane lifting, a slipway or a dry dock. The different load-out options will be compared in the section "Opportunities for cost reduction".

5.1. Sensitivity analysis

The sensitivity analysis consists of varying an input parameter over a range of possible values. All other values are kept at the same value corresponding to the reference case. By performing such sensitivity analysis, the effect of uncertain estimates on the LCOE value can be investigated.

Structure steel.

[40] testifies the high volatility of the worldwide raw steel price during the last 7 years. In early 2009 the maximum price value of steel was attained, reaching 1,265 USD/tonne. In 2016 the lowest price was observed at 90 USD/tonne. Nowadays, the price is around 312.50 USD/tonne. Compared to the reference value of today (321.5 USD/tonne), the volatility of the price of steel observed during the last 7 years corresponds to a difference of 405.44% with the highest price and 28,80% with the lowest price. The volatility presented on the raw steel price has been applied in the sensitive analysis of the cost of manufactured steel for shipbuilding applications, see Table 5.1.

Steel price [€/tonne]	LCOE [c€/kWh]	Increment of LCOE [%]
6,000	84.33	+42.90
5,500	80.18	+35.87
5,000	76.03	+28.84
4,500	71.88	+21.81
4,000	67.73	+14.78
3,500	63.58	+7.74
2,950	**59.01**	**0**
2,500	55.27	-6.34
2,000	51.12	-13.37

Table 5.1. Sensitivity analysis for steel price [€/tonne]. The reference case is shown in type blood.

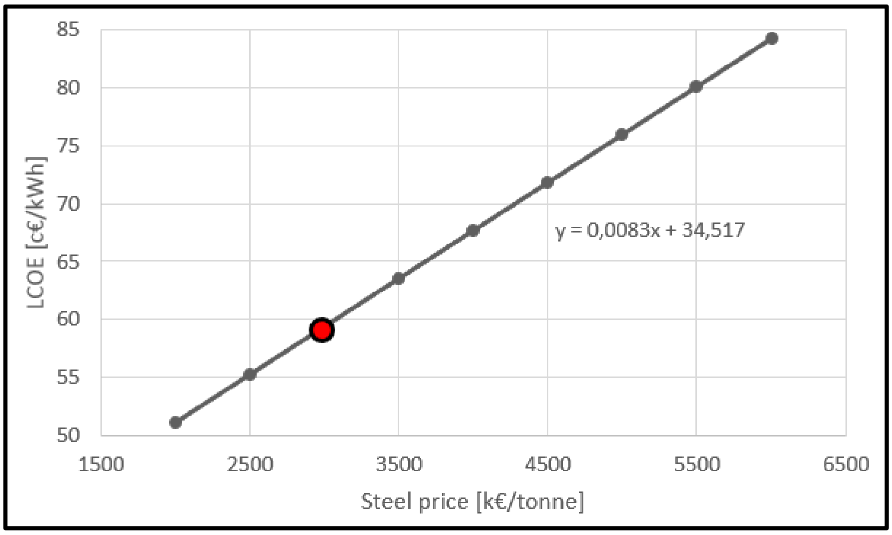


Figure 5.3. Graph of the LOCE [c€/kWh] as a function of the steel price [k€/tonne]. The reference case is shown in red.

There exists a linear relationship between the steel price and the LCOE as can be seen in Figure 5.3. The LCOE increases with a factor of 0.0083 per unit of steel price.

Turbine and valves.

The range of cost estimates for the turbine and valves have been set to ±20% of the reference value as a first approach, 472k€, see Table 5.2.

Cost of the turbine and valves price [k€]	LCOE [c€/kWh]	Increment of LCOE [%]

565.4	60.90	+3.20
500	59.58	+0.97
472	**59.01**	**0**
450	58.56	-0.76
377.6	57.10	-3.20

Table 5.2. Sensitivity analysis for the cost of the turbine and valves [k€]. The reference case is shown in type blood.

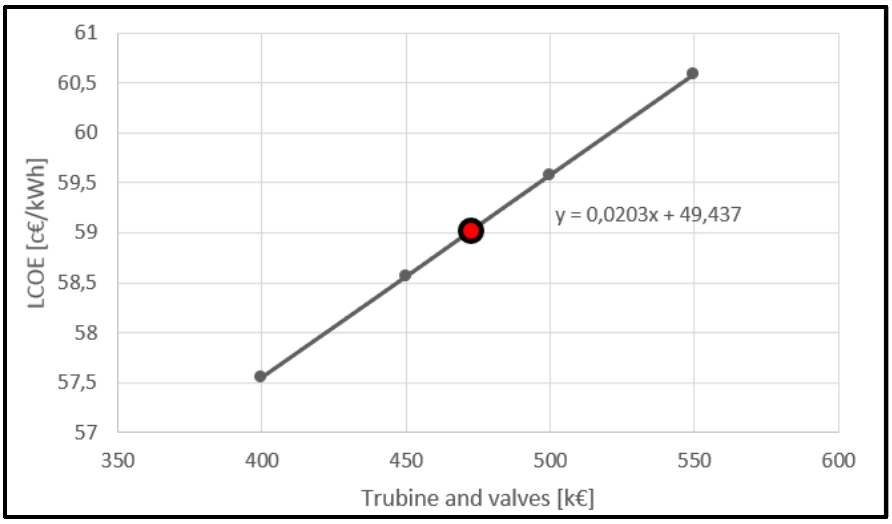


Figure 5.4. Graph of the LOCE [c€/kWh] as a function of the cost of the turbine and valves [k€]. The reference case is shown in red.

The relation between the turbine & valves and LCOE is also lineal, as can be seen in Figure 5.4. The LCOE increases with a factor of 0.0203 per k€ of turbine and valve cost.

Generator.

The range was also set to ±20% of the reference value as a first approach, 264k€. See Table 5.3.

Cost of the generator[k€]	LCOE [c€/kWh]	Increment of LCOE [%]
316.8	60.08	+1.81
275	59.23	+0.04
264	**59.01**	**0**
211.2	57.94	-1.81
150	56.70	-3.91

Table 5.3. Sensitivity analysis for the cost of the turbine and valves [k€]. The reference case is shown in type blood.

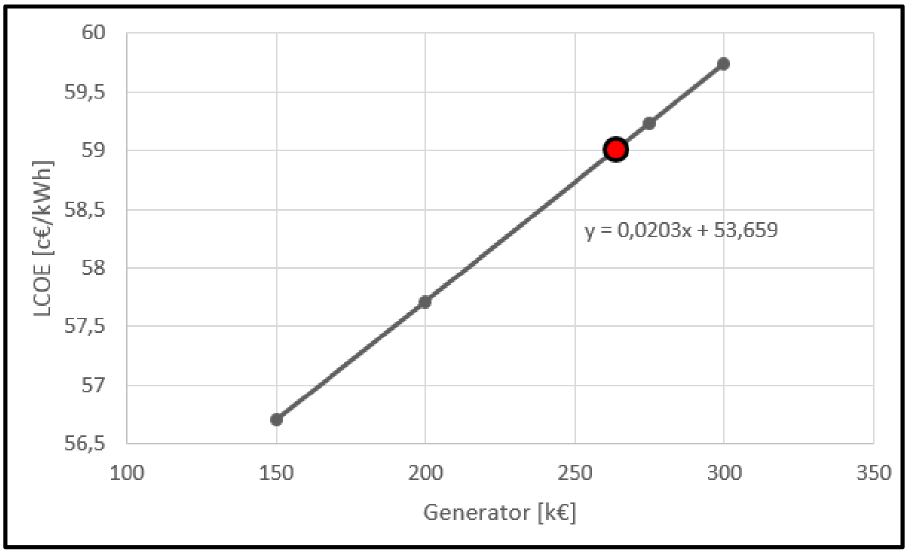


Figure 5.5.Graph of the LOCE [c€/kWh] as a function of the cost of the turbine and valves [k€]. The reference case is shown in red.

Mooring system and anchor.

As a first rough approximation, the mooring length may be determined as 1.91 times greater than the water depth. If this coefficient is applied to 40m water depth, the mooring length becomes 76.40m. The minimum value tested will be 1.4 times the water depth. See Table 5.4 and Figure 5.6.

Mooring length [m]	LCOE [c€/kWh]	Increment of LCOE [%]
153	**59.01**	**0**
125	58.59	-0.71
100	58.21	-1.36
76.40	57.86	-1.95
50	57.46	-2.63

Table 5.4. Sensitivity analysis for the cost of the mooring system [k€]. The reference case is shown in type blood.

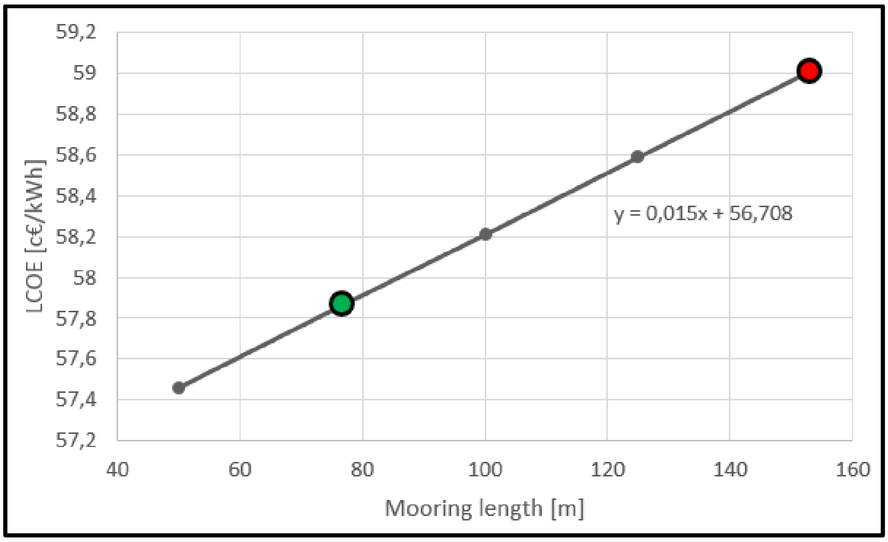


Figure 5.6. Graph of the LOCE [c€/kWh] as a function of the length of the mooring system [m]. The reference case is shown in red, while the approximate suitable length of the moorings is shown in green.

In the reference case study, the anchor weight is 9.07 tonnes. Similarly, to the mooring length, a very approximate coefficient of 0.059 can be multiplied to the water depth. For a water depth of 40m, an indicative anchor weight can be estimated at 2.37 tonnes. See Table 5.5. and Figure 5.7.

Anchor weight [tonnes]	LCOE [c€/kWh]	Increment of LCOE [%]
9.07	**59.01**	**0**
7	58.56	-0.76
5	58.13	-1.49
2.37	57.57	-2.44
2	57.49	-2.58

Table 5.5. Sensitivity analysis for the cost of the anchor weight [tonnes]. The reference case is shown in type blood.

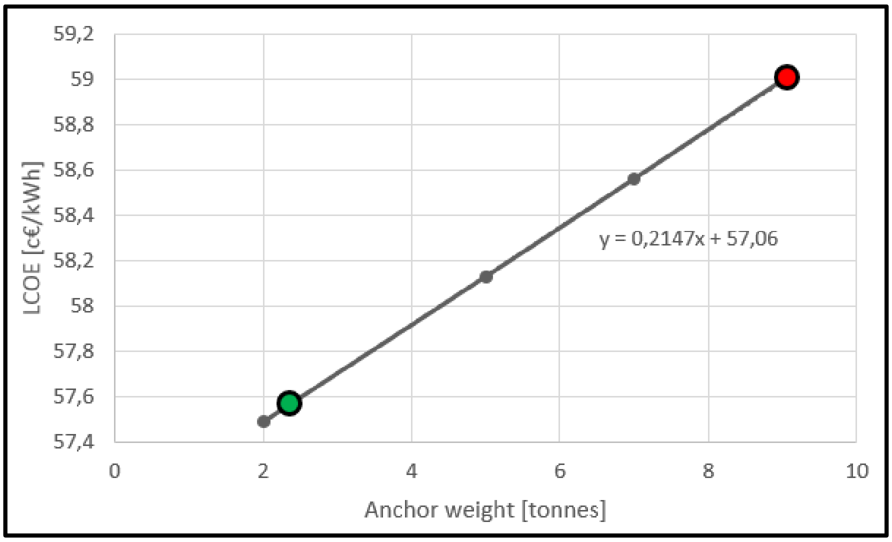


Figure 5.7. Graph of the LOCE [c€/kWh] as a function of the cost of the anchor weight [tonnes]. The reference case is shown in red, while the approximate suitable length of the moorings is shown in green.

Distance between devices.

Considering that further studies will be required to define the mooring system design, the distance between devices will also be adapted and included in the sensitivity analysis. See Table 5.6 and Figure 5.8.

Distance between devices [m]	LCOE [c€/kWh]	Increment of LCOE [%]
200	59.54	+0.89
175	59.27	+0.44
150	**59.01**	**0**
125	58.75	-0.44
100	58.49	-0.88

Table 5.6. Sensitivity analysis for the cost of distance between devices [m]. The reference case is shown in type blood.

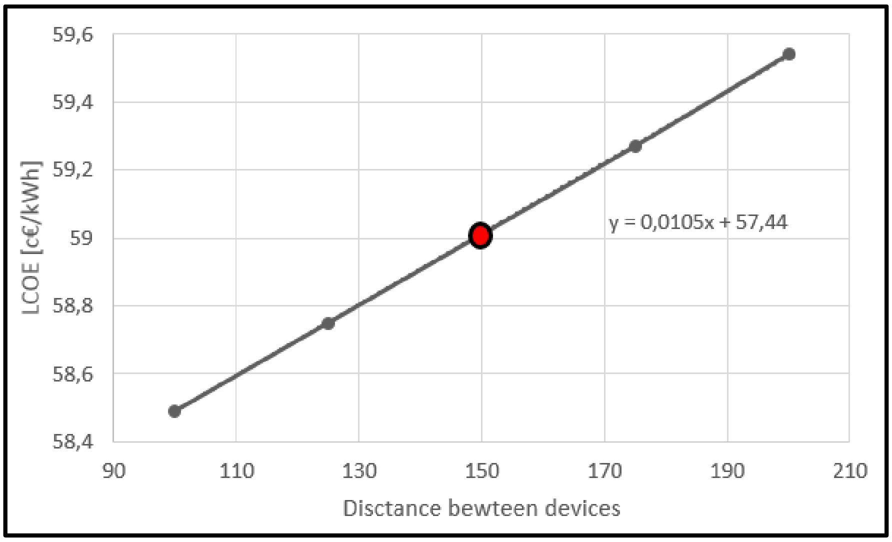


Figure 5.8. Graph of the LOCE [c€/kWh] as a function of the distance between devices [m]. The reference case is shown in red.

Distance from site to shore.

The reference case study has selected the location of Aguçadora which is 4,5 km away from shore. The sensitivity analysis below is dealing with the distance from shore to site. The maximum distance that assumed is 50 km and the minimum distance to shore was chosen to be 3km based on practical and economic constraints already accepted for the offshore wind sector. The same wave resource is assumed independently of the distance to shore, see Table 5.7 and Figure 5.9.

Distance from site to shore [km]	LCOE [c€/kWh]	Increment of LCOE [%]
50	78.01	+32.20
25	66.66	+12.96
10	60.94	+3.27
6	59.53	+0.88
4.5	**59.01**	**0**
3	58.50	-0.86

Table 5.7. Sensitivity analysis for the cost of distance from site to shore [m]. The reference case is shown in type blood.

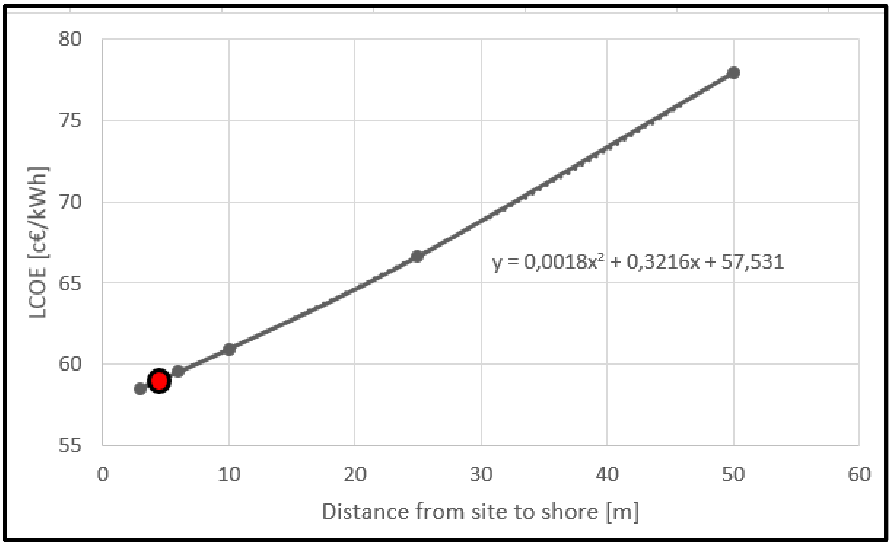


Figure 5.9. Graph of the LOCE [c€/kWh] as a function of the distance from shore to site [m]. The reference case is shown in red.

OPEX.

The OPEX found for the reference case is within the range of values expected for a wave farm at a pre-commercial stage (208.10 c€/kW/year). In the future, the target for wave energy plants is to reduce the OPEX to the offshore wind farms value (80 c€/kW/year). The sensitivity analysis depicted in Table 24 investigates the reduction of the OPEX from the actual reference value to the target value of offshore wind. See Table 5.8 and Figure 5.10.

OPEX [c€/kW/year]	LCOE [c€/kWh]	Increment of LCOE [%]
208.10	**59.01**	**0**
170	56.81	-3.73
140	55.08	-6.66
110	53.35	-9.59
80	51.62	-12.52

Table 5.8. Sensitivity analysis for OPEX [c€/kW/year]. The reference case is shown in type blood.

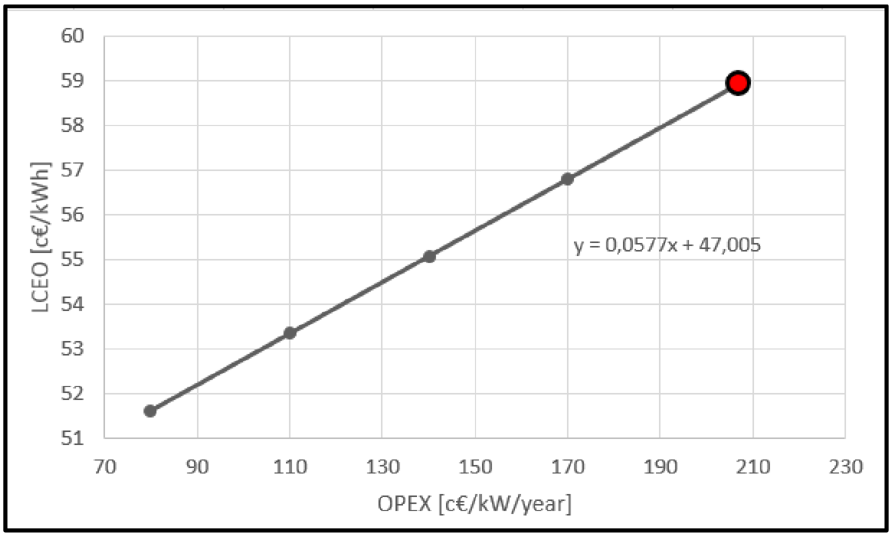


Figure 5.10. Graph of the LOCE [c€/kWh] as a function of the OPEX [c€/kW/year]]. The reference case is shown in red.

Sensitivity analysis summary

In Table 5.9 and Figure 5.11 the relative variation of each factor considered for the previous sensitivity analysis is compiled together to show how the LCOE vary with the different ranges.

	Minimum value	Reference value	Maximum vale	**Minimum variation LCOE [%]**	**Maximum variation LCOE [%]**
Steel price [k€/tonne]	2,000	2,950	6,000	**-13.37**	**+42.90**
Turbine [k€]	377.6	472	566.4	**-3.24**	**+3.24**
Generator [k€]	211.2	264	316.8	**-1.80**	**+1.80**
Mooring length [m]	50	153	153	**-2.63**	**0.00**
Anchor weight [tonnes]	2	9.07	9.07	**-2.58**	**0.00**
Distance between devices [m]	100	150	200	**-0.88**	**+0.89**
Distance from shore to site [km]	3	4.5	50	**-0.86**	**+32.20**
OPEX [c€/Kw/year]	80	208.10	208.10	**-12.52**	**0.00**

Table 5.9. Summarize of the LCOE variation (%) for the minimum and maximum values tested in the sensitivity analysis.

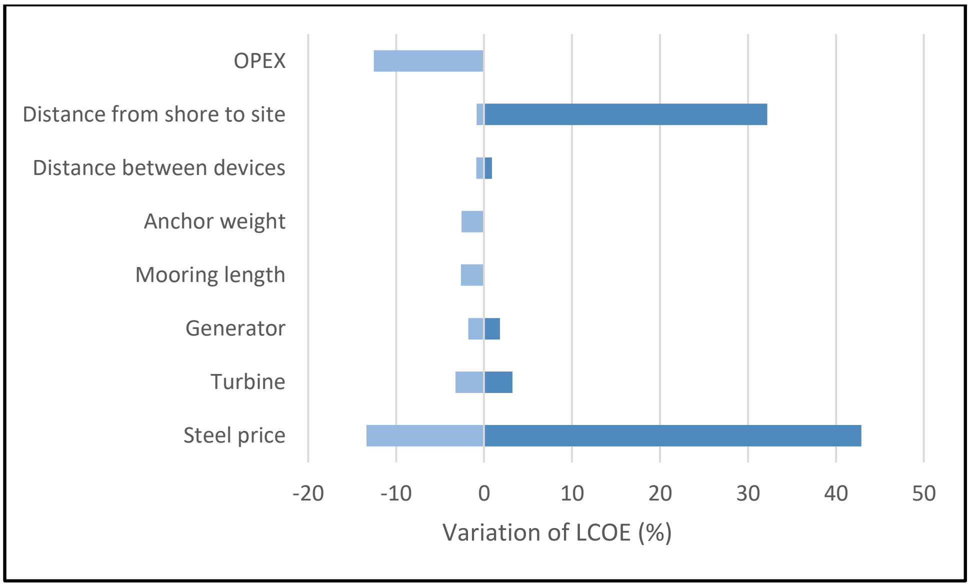


Figure 5.11. Graph showing the minimum and maximum LOCE variation for the values tested in the sensitivity analysis.

Sensitivity analysis conclusions

Table 5.9 and Figure 5.11 summarize the main findings of the sensitivity analysis.

The component that introduces more variability to the final cost of the farm is the steel price, implying a potential variation of +42.9% and -13.37 % of the LCOE. This high variability is attached to the high volatility price of the raw steel in the market. In the future, it would be worth looking at alternative materials such as composites and concrete, in order to investigate their influence on the cost of UGEN and see whether the market volatility could be mitigated.

Regarding the distance from site to shore a high increment of the LCOE (+32.20%) is observed. Since offshore wind farms with distance from shore of 50km are already in the pipeline of future projects, WEC farms may also target such distances to shore. Although actually the LCOE would be too high, 78.0 c€/kWh. The reduction of the cost of the components and the installation process at long distances from shore would convert this distance to a profitable option for WECs as well.

The OPEX has been computed as a percentage of the CAPEX. More detailed studies are required to determine this cost. However, the target of the UGEN is to have an OPEX of similar magnitude than that of the OPEX for offshore wind farms, around 80 c€/kW/year. If this goal was achieved the LCOE would be reduced a -12.52%.

The cost of the generator and the turbine has been estimated using the empirical algorithm proposed in [34]. Although a variability of the cost ±20% has been set for both components, the total variation of the LCOE has been found to be ±5.04%. The final variation of the LCOE is not high but will require to be revised with real quotations of suppliers.

The mooring length and anchor weight are expected to be reduced when the new study of the new mooring system will be performed, for a water depth of 40m. The estimation of the total decrease of the LCOE has been found to be -5.21%.

The distance between devices has been found to not have a high impact on the final LCOE value, although the final distance presents uncertainty at this early stage and will require refinements.

Finally, the sum of all cost reductions would imply a LCOE decrease of 37.88%. Resulting a LCOE of 36.66 c€/kWh.

5.2. Opportunities for cost reduction

Installation of the main structure.

The high weight of the device (410 tonnes) represents a major challenge for load-out operation of the device from dock to sea. The project team has suggested three options to accomplish this operation, using a crane to lift the device, a slipway or a dry dock.

In Figure 5.12, a flow chart of the installation process of the UGEN main structure is shown.

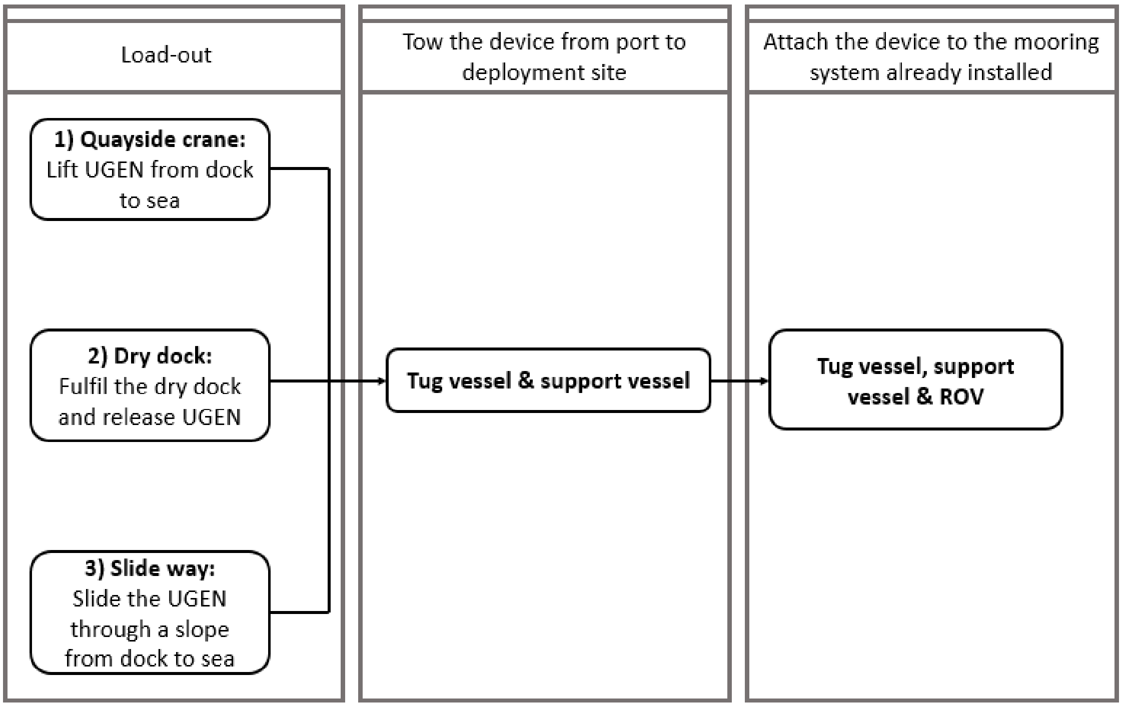


Figure 5.12. Flow chart of the main structure installation considering the three options proposed to transport the device from dock to sea

The costs associated to the three proposed load-out operations are shown in Table 5.10.

	Quayside crane	Slide way	Dry dock
Reference	[37]	[36]	[42, 43, 44]
Price	Mob. = 330 k€ Day rate = 9.8 k€/day	1st day = 2.675 k€ + Day = 0.535 k€/day	1st day = 1.145 k€ + Day = 0.691 k€/day
Days	0.69 days/device 27.6 days/farm	5 days/device 200 days/farm	5 days/device 200 days/farm
Cost of the installation of the main structure [k€]	591.66	192.60	45.91
LCOE [c€/kWh]	59.01	58.61 (-0.68 %)	58.53 (-0.81 %)

Table 5.10. Comparison of the costs and LCOE associated to the three options proposed to transport the device from dock to sea.

The dry dock presents the lowest cost, reducing the LCOE by 0.81% while the slipway alternative reduces the LCOE by 0.68% when compared to the lift-away option.

However, both options present uncertainty. The company that has quoted for the slide way [36], notifies that the structure is probably too big to use the slipway. Regarding the dry dock, the draft of the device, 13m, is unusual for the length of the device 30m comparing to the dimensions of typical vessels making use of similar dry-docks. After contacting to a local dry docks, the maximum draft available was found to be 6m. Carrying out the load-out operation in a dry dock for larger vessels would increase the cost.

Electrical connection equipment.

The electrical array layout for the reference case has been defined with 5 clusters of 8 devices. The clusters are connected to a junction box which is at the same time connected to a main junction box by a static cable. Finally, the main junction box is connected to the shore using an export static cable, see Figure 4.6.

The other option that has been proposed for the project team is to connect the 5 clusters of 8 devices directly to shore by means of 5 export cables in series, see Figure 5.13.

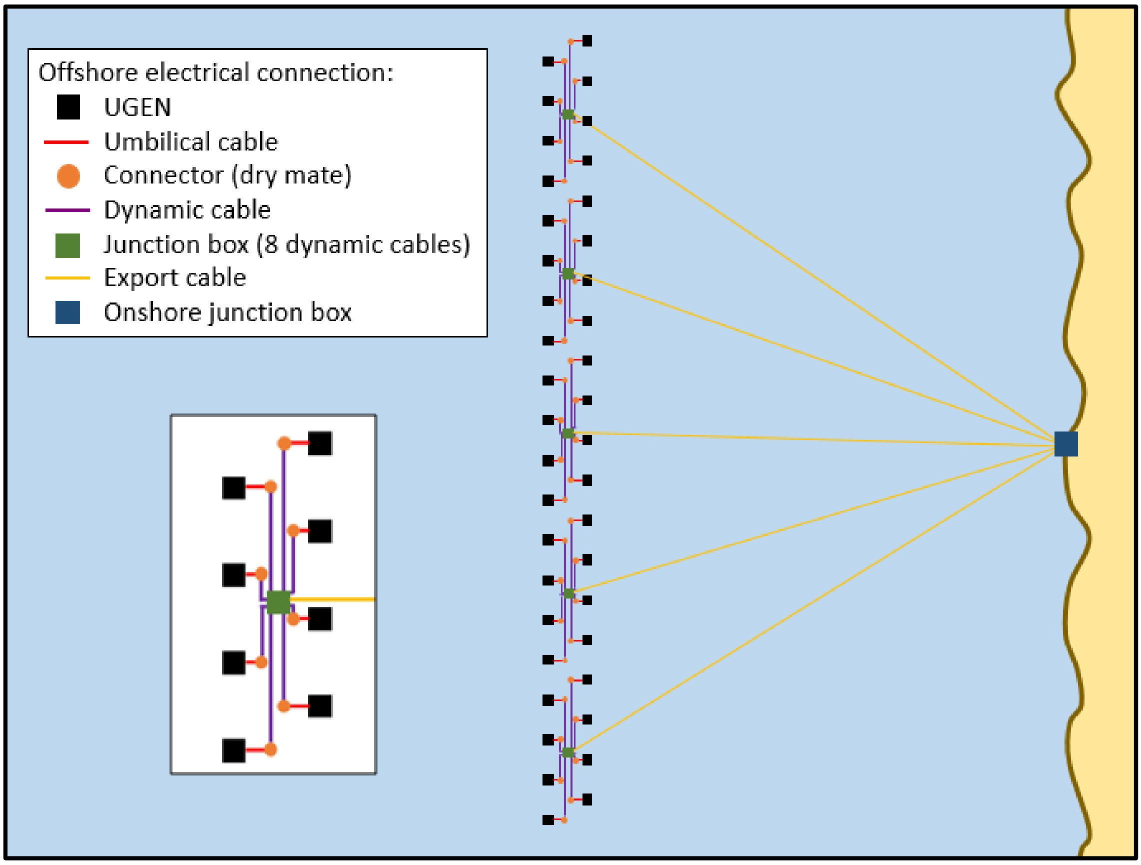


Figure 5.13. Alternative electrical array layout.

	Reference case	Alternative electrical array layout
Components	40 umbilical cables 40 connectors (dry mate) 40 dynamic cables 5 junction boxes 5 inter-array static cables 1 main junction box 1 export static cable	40 umbilical cables 40 connectors (dry mate) 40 dynamic cables 5 junction boxes 5 export static cables Total length of the 5 Export cables=23.92 km 1 onshore junction box
Price	300 k€/km umbilical cable 150 k€/unit connectors (dry mate) 100 k€/km dynamic cable 150 k€/unit junction box 100 k€/km static cable 250 k€/unit main junction box 150 k€/km export cable 250 k€/unit onshore junction box	

Total cost of the electrical connection equipment [k€]	9,992	12,515
Total cost of installation of electrical connection [k€]	13,982	13,651
LCOE [c€/kWh]	59.01	59.95 (+1.59%)

Table 5.11. Comparison of the costs and LCOE associated to the two options proposed for the electrical connection array.

The alternative electrical layout solution leads to a higher cost than the reference case solution. With the alternative solution, the LCOE has marginally increased by 1.59% which favours the reference case electrical layout. However, the difference between the two electrical layout options appears to be relatively small. Given the uncertainty in the underlying cost estimates, more detailed analysis to compare the two options are advisable before making a final decision.

Submergence of the device.

If the floater can be submerged in anticipation of extreme weather conditions, it is envisaged that expected load reductions of the submerged OWC spar buoy would potentially allow reduction in the thickness of the steel structure of the floater as well as the robustness of the mooring system. As an initial guess, it is hoped that 30% reduction of the steel mass structure may be attained. The final mass of the device would be 287 tonnes, see Table 5.12.

	Reference case	Submergence
Steel mass	410 tonnes	287 tonnes
Price	2.950 k€/tonnes	
Cost of the structure [k€]	48,380	33,866
LCOE [c€/kWh]	59.01	51.66 (-12.45%)

Table 5.12. Comparison of the costs and LCOE associated to the reference case and the submergence option of the device.

A reduction of the LCOE of 12.45% would be achieved by incorporating the submergence option of the device. This gain is very significant and should strongly encourage investigating further the implementation of a submergence process for the UGEN. Nevertheless, additional costs (and possibly power consumption) associated with the equipment required for submerging the device should deteriorate this preliminary positive LCOE reduction.

Reduction of size.

In the future, design iterations are expected to converge to an optimal shape of the floater which could require less material while maintaining the same level of power production performance. Assuming 20% of reduction in the mass of steel can be achieved, the LCOE can decrease by 8.30%, as depicted Table 5.13.

	Reference case	Future dimension reduction
Steel mass	410 tonnes	328 tonnes
Price	2.950 k€/tonnes	
Cost of the structure [k€]	48,380	38,704
LCOE [c€/kWh]	59.01	54.11 (-8.30%)

Table 5.13. Comparison of the costs and LCOE associated to the reference case and the future dimension reduction.

Change material.

An alternative route towards cost reductions that is worth investigating is to consider changing the main structure material. While steel is extensively used in offshore applications, other suitable material such as concrete and other composite (e.g fiber reinforced plastics) may offer credible solutions. Each material has its own pros and cons but ultimately, if the material choice together with a proper design process brings the main structure cost down to 50%, the LCOE can also be diminished by 20% as seen in Table 5.14.

	Reference case	Future material
Cost of the structure [k€]	48,380	24,190
LCOE [c€/kWh]	59.01	46.77 (-20.74%)

Table 5.14. Comparison of the costs and LCOE associated to the reference case and the future possible material.

Bulk factor for the components of the UGEN.

The bulk factor refers to the discount normally applied by suppliers if the purchase of products or components is higher than a certain number of units. The discount is normally greater as more units are purchased. The costs associated to the steel structure were obtained through a raw quotation for a single UGEN unit construction provided by a Portuguese shipyard [36] and reference [39]. Since it is intended to produce a series of 40 UGEN units, a bulk factor is likely to be applied to the invoice reflecting the large order. Analogously, the turbine and generator costs were determined by empirical algorithms ignoring the effect of production in series. Future suppliers are expected to offer a bulk discount for the 40 turbines and generators required for the farm. Assuming a maximum bulk factor of 10%, a reduction of the LCOE of 6.67%, see Table 5.15.

	Reference case	Bulk discount
Cost of the structure and the PTO system [k€]	Steel = 48,380 Turbine = 18,880 Generator = 10,560 TOTAL = 77,820	Steel = 43,542 Turbine = 16,992 Generator = 9,504 TOTAL = 70,038
LCOE [c€/kWh]	59.01	55.07 (-6.67%)

Table 5.15. Comparison of the costs and LCOE associated to the reference case and with a bulk discount for the components of the UGEN.

Learning process (installation and weather downtime).

As operational experience accumulates, the time required to transport, position, attach and install the UGEN units is expected to decrease mostly because of increasing knowledge and tuning of the process by all actors from the supply chain to the marine operators.

Regarding the installation process, a reduction of the total time of 30% has been considered, implying a reduction of -3.81% of the LCOE, see Table 5.16.

	Reference case	Learning process
Mooring system	8 hours/mooring system	5.6 hours/mooring system
Electrical connection equipment	Umbilical + dynamic = 10 hours /unit Static or export = 12 hours/unit Junction box = 12 hours/unit	Umbilical + dynamic = 7 hours /unit Static or export = 8.4 hours/unit Junction box = 8.4 hours/unit
Main structure	3 hours/unit	2.1 hours/unit
LCOE [c€/kWh]	59.01	56.76 (-3.81%)

Table 5.16. Comparison of the costs and LCOE associated to the reference case and taking into account the learning process of the installation operation.

The weather downtime.

Under the reference case scenario, it was assumed that the maximum significant wave height for the installation vessels is 1.5m. The future implementation of tailored-made technologies and vessels to perform the UGEN installation may rise the maximum significant wave height threshold up to 2 – 2.5m. This leads to an increase of 20% in the number of accessible days where the installation of the device can be performed. However, the impact on the LCOE is very limited and also negligible (reduction of 0.85%) as seen in Table 5.18.

	Reference case	Increase of accessible days
Inaccessible days	47%	38%
LCOE [c€/kWh]	59.01	58.51 (-0.85%)

Table 5.17. Comparison of the costs and LCOE associated to the reference case and taking into account the maximum significant wave height to 2 – 2.5m.

Power matrix.

The AEP calculation for the reference case considers that all estimated average power production performance computed in the power matrix are achieved in all sea-states. In practise, WEC technologies would typically turn to a survival mode under extreme conditions and, hence are unlikely to generate electricity for very energetic sea-states (similar to the cut-off speed effect for wind turbines). It is expected to reach higher operational sea-state conditions where the devices can still generate as the technology matures. At first the UGEN is planned to switch to survival mode with a sea-state of Hs=6.5m and Te=12.5 seconds while, in the long-term, it may be achievable to generate electricity even for the maximum sea state observed in Aguçadora Hs=10.5 and Te=16.5 seconds as it has been assumed in the reference case scenario. See Table 5.18.

Sea state	LCOE [c€/kWh]
Hs=6.5m Te=12.5sec	60.97 (+3.32%)
Hs=7.5m Te=13.5sec	59.71 (+1.18%)
Hs=8.5m Te=14.5sec	59.16 (+0.25%)
Hs=9.5m Te=15.5sec	59.06 (+0.08%)
Hs=10.5m Te=16.5sec	**59.01**

Table 5.18. Comparison of the costs and LCOE associated to the reference case and taking into account the survival mode in extreme conditions.

Learning rate of the wave energy industry.

The wave energy industry is a novel technology. The WEC are still in a pre-commercial stage, with margin to improve electrical generation and reduce costs. The comparison in Table 5.19 summarize the expected progression of the wave energy industry due to learning procedures, materials and designs through the next years.

This learning rate study is a function of the expected wave energy deployment during the following years, until 2050. [47] suggests a deployment rate curve similar to onshore and offshore wind, even though the former is at a more advanced stage of development. The actual levels of cumulative capacity for onshore and offshore wind from 1990 to 2030 have been extracted from [46]. The reference scenario presented in [47] depict 0.7 GW in 2020, 11 GW in 2030 and 80 GW installed by 2050. The wave energy deployed has been finally set to 0.7 GW in 2020, with a growth rate of 17%, what means 79 GW of wave energy deployed in 2050.

The following learning rates for the wave energy industry for future years have been assumed from reference [45].

- Structure and prime mover = 9%
- Power take-off = 7%
- Station-keeping = 12%
- Connection = 1%
- Installation = 8%
- O&M = 12%

The rest of learning rates have been all set to 5%, as follows:

- Project management, studies, etc. = 5%
- Wave specific electrical connection = 5%
- Capacity factor = 5%
- Discount rate = 5%
- Construction period = 5%
- Project lifetime = 5%

Finally, the expected increment of the price for the components conforming the UGEN per year have been retrieved from reference [46].

- Vessels = -0.52%
- Labour = 2%
- Electric machinery = -1.50%
- Metal structures = 3%
- Electronic apparatus = -1.50%
- Copper = 3%
- Consumer price index (CPI) = 2%
- Electricity cost = 3%

The cost evolution from today until 2050 is shown in Table 5.19.

	Actual	2020	2025	2030	2040	2050
LCOE [c€/kWh]	59.01	53.92	28.76	24.64	18.78	15.67
CAPEX [c€/kWh]	46.78	44.73	23.03	19.53	14.66	12.14
OPEX [c€/kWh]	12	9.19	5.73	5.11	4.12	3.53

Table 5.19. LCOE evolution from actuality to 2050 for the learning rates and cost indices of [45, 46].

The learning rates for wave energy presented in [45] vary between 5 and 12%. The learning rates suggested in [47, 48] are 8-10% for wind industry. Specifically, for offshore wind: 9% [47] and 5-10% [48]. According to [47] ocean energy presents a similar learning rate to offshore wind. On the other hand, the average learning rate for solar PV is approximately 20% [47,48]. This higher learning rate for solar PV is expected due to it is a high-tech industry with large basic R&D in materials and components.

Immediate and long term opportunities for LCOE reduction

From the analysis above we can distinguish between immediate and long term timeframes concerning the cost reduction of UGEN.

There are immediate opportunities to reduce costs to the UGEN system, firstly bulk factor has a significant effect on cost reduction for UGEN, this is because discounts would be applied once a bulk order is placed for the components required for the UGEN farm. Further to this, the experience gained by the technicians from installing the UGEN systems would reduce costs, however this reduction would not be immediate, instead experience accumulated would reduce costs accordingly over time.

Another issue presented was that of the electrical array layout, more analysis is needed in order to know which array layout is more suitable for the UGEN system. Once this has been presented and implemented the cost reduction related to the electrical connection equipment could be analysed and rebuild in order to find a suitable solution.

On the other hand, there are several long term solutions presented in this thesis. The device itself will be the central aspect to change for cost reduction through submergence of the device, reduction of size and/or change of material. This is due to a reduction in manufacturing costs, however analysis into the optimal UGEN system will take time and experience accumulated through simulations and tests. In the same manner, further analysis is needed to widen the range of the UGEN system in order to increase the AEP which results in an LCOE reduction. Although these analyses require time to understand the durability of the device in stormy conditions.

One cost that could be proposed, to eventually reduce further costs in the future, would be to create a specific load-out operation designed specifically for the UGEN, in the place of using inferior and costly ways to deploy the UGEN system. This should be put in place if the number of devices planned to be built was high enough to make this solution profitable.

Finally, the learning rate of wave energy industry is strongly related to the UGEN LCOE. The future perspective of the UGEN will depend on the cost decrease and the AEP increase resultant of this rate.

Conclusions

In 1990s the first floating OWCs WEC appeared, arising new concepts for the wave energy industry. In 2010 the UGEN concept was presented, an OWC enclosed into a floating structure in contact with the outer water. The UGEN concept relies on three well known concepts: The Salter's duck device, the U-tank used to stabilize the vessels while sailing and the Wells turbine which has been extensively used in OWC devices through the last 30 years.

As it has been explained the device finally presents a different shape of the Salter's duck. While the duck of the Salter's duck faces the incoming waves, inversely it is the vertical side of the UGEN that faces the incoming waves. Analogously, the UGEN maximizes the roll motion of the device, while the U-tank has the aim of stabilizing the hull WEC during marine transportation.

Regarding the Wells turbine, it appeared in 1976, and since then, has been the most well-known and utilized self-rectifying turbine for OWCs devices. But other self-rectifying turbines are being considered, specifically the biradial turbine. The biradial turbine is being developed at Instituto Superior Técnico and presents a higher efficiency and a wider range of working pressures than the Wells turbine. The implementation of this new turbine could enlarge the power generation of the UGEN.

In 2010 an experimental program with a 1:16 scaled model of the UGEN wave energy converter was tested. The experimental results showed two distinct frequency ranges with large dynamic amplification of the fluid motion in the U-tank (oscillating water column).

Afterwards, the optimization of the device was accomplished dividing the problem into two parts. A main problem with the floater main dimensions and an internal problem, where the turbine characteristics and device mass distribution are optimized. The actual dimensions of the device were found for the following objective function: annual-averaged power output divided for the mass of steel of the device.

Once the capability of the device to generate electrical power was proven, an analysis of the total cost of the UGEN was required in order to evaluate the potential profitability of the device and guide the technology development.

The LCOE is an economic assessment of the average total cost to build, operate and decommission a power-generating device over its lifetime divided by the total energy output of the device over that lifetime.

The LCOE value for a reference 20 MW farm composed by 40 UGENs was found to be 59.01 c€/kWh =590.1 €/MWh. The comparison with the literature, [25], has shown that the device is still at a pre-commercial stage.

The LOCE is divided in three major cost components: the CAPEX (5,946 €/kW), the OPEX (208.10 €/kW/h) and the decommission costs (297.29 €/kW).

The OPEX was considered as a percentage of the LCOE, due to the lack of operational data. In the same manner, the decommissioning costs were set as a percentage, since very few offshore renewable energy power plants have been dismantled to-date and no detailed information about these costs can be found in the literature.

The major cost of the CAPEX is the WEC manufacturing (4,388 €/kW), followed by the assembly, installation & commissioning (899 €/kW), the electrical connection equipment (496 €/kW) and the project development (150 €/kW).

In a more detailed view, the percentages of the CAPEX are: structure (32.21%), PTO (19.60%), installation cost (11.96%), electrical connection components (6.60%), mooring system (4.78%) and the project development (2.00%) and others.

Comparing to the literature, [25], the structure and PTO are slightly higher, while the installation cost and electrical connection are lower than the reference values which may be explained by the low distance from site to shore of the farm (4.5km).

Main drivers of the LCOE

The main driver of the LCOE is the structure of the UGEN. The cost of steel has been determined by a quotation of a Portuguese shipyard, 2,950 €/tonne [36]. However, the exact mass of the device will become more accurate when the final scantling of the device will be available and presented to the shipyard.

The cost of the PTO (electro-mechanical components converting mechanical power into electricity) was determined using an empirical algorithm proposed in [34]. Further quotations of manufacture suppliers will be required to get a tailored and up-to-date cost estimate.

The installation of the electrical connection represents 78% of the total installation cost, followed by the mooring system 14% and the main structure 8%.

Sensitivity analysis

The sensitivity analysis has revealed a strong risk attached to the cost of the structure's material. The high percentage of the cost structure above the LCOE attached to the volatility cost of steel can represent an increment of the LOCE up to a 42.90%. This situation raises the possibility of pursuing suitable substitute materials, with less variable cost in the market to make UGEN a feasible power generator.

The sensitivity analysis has also shown that the distance from shore to site should preferably remain small, around 4.5km. The UGEN is still at an early stage and cannot be profitable at the distances being considered today for offshore wind farms, up to 50km offshore.

The OPEX value was found to be 208.10 c€/kW/year for the reference case. The target for wave energy plants is to reduce the OPEX to the offshore wind farm value, 80 c€/kW/year, that would imply a reduction of the LCOE of 12.52%.

Opportunities for cost reduction

Opportunities for costs reductions have been investigated using the LCOE model in order to identify the alternative options that may lead to a significant decrease of the LCOE.

The load-out operation has demonstrated that the dry dock (-0.81% LCOE) and slide way (-0.68%) might be cheaper options than the quayside crane. Although, the large dimensions of the UGEN may prevent a project developer from selecting these alternative load-out strategies. The different possible solutions for the load-out operation would reduce the UGEN LCOE.

The electrical connection array connecting each cluster with shore, leads to a higher cost than the reference solution connecting the farm with site using a single export cable. However, the difference of the LCOE appears to be relatively small, which could change given the uncertainty of the cost components and installation. Further studies will be required to determine other feasible electrical layout configurations.

The incorporation of the submergence option of the device could reduce the LCOE by 12.45% assuming that it results in saving about 30% of the steel used in the structure. The implementation of this option should be encouraged, although additional costs are expected associated to the equipment required submerge the device. This would diminish the potential LCOE reduction impact.

The reduction of size may be envisioned in the future and could reduce the LCOE value by 8.30% if a mass reduction of a 20% was achieved assuming the UGEN machine would maintain its power production performance at the same level. In the same way, an alternative material that reduces the cost of the structure by a 50% would imply a 20% LCOE reduction.

A bulk factor is expected to be available from the suppliers due to a large number of purchased materials/components. Assuming a 10% discount on the steel, turbine and generator the LCOE reduction would be of 6.67%.

Future perspectives for the UGEN

The actual stage of the UGEN and the WECs industry are still in process of development. The continuous optimization and analysis of the UGEN is expected to reduce its LOCE. Analogously, the WEC industry is expected to present cost reductions due to advances in technological understanding. This understanding is based on the accumulated experience of overall sector due to the projection of an increasing and cumulative number of projects, devices, materials and different alternatives. A simplified analysis of the learning rate can be seen in Table 5.19. This indicates that a LCOE of 15.67 c€/kWh may be foreseen by 2050 assuming a learning rate of 5-10%. A detailed study of the learning rates of the WECs industry and the its final impact on the UGEN LCOE will be required in order to evaluate the future costs projection of the UGEN concept under different market conditions and scenarios.

A research of suitable materials to substitute steel as the structure's material must be completed, as the volatility of the raw steel price shown in the "Sensitivity analysis conclusions" section and the high mass of the device, 410 tones, are key-factors for the cost reduction and the profitability of the device.

The engineering analysis must be rebuilt, in order to recalculate the UGEN and mooring system dimensions for the deployment site of the farm at the Aguçadora site.

The uncertainty attached to the final design and components of the UGEN has made it not possible to gather the failure rates of the components from the suppliers. Due to this impossibility the OPEX has been computed as a direct percentage of the CAPEX, see “OPEX calculation”. The replacement of the simplified model of the OPEX by a more elaborated O&M model exploiting the failure rates and the estimated repair time would lead to a more accurate LCOE.

The MatLab routine must be rebuilt in order to obtain a more reliable LCOE on further optimizations of UGEN. After comparison with the WavEC techno-economic model, the costs involved with the project development, the electrical connection equipment, the installation & commissioning and the monitoring & miscellaneous equipment invoices must be readjusted. The total sum of these costs are 31,164 k€ in the WavEC techno-economic model while the Matlab routine invoices 2,500 k€ in concept of others. Further improvements could mean: include decommission costs and resetting the OPEX (3.5-5 % of CAPEX) [25, 32, 33].

Finally, as detailed before, the LCOE value for the farm was found to be 59.01 c€/kWh = 590.1 €/MWh. Compared to other renewable sources the UGEN still requires further developments and optimizations in order to achieve market competitiveness. The LCOE [€/MWh] for different type of renewable energies are [51]: marine wave 315 - 560, marine tidal 290 – 505, wind offshore 145 – 365, wind onshore 55 – 250, PV 85 – 335, geothermal – binary plant 85 – 270 and Solar thermoelectric generator – tower & heliostat with storage 125 – 280.

Compared to other WECs [32] the LCOE value for the UGEN requires further optimizations and reductions can be concluded from the following example: Pelamis 441 €/MWh, AquabuOY 105.85 €/MWh and WaveDragon 317.55 €/MWh.

For commercial competitiveness the LCOE has to be reduced from 59.10 to 10 c€/kWh, meaning an 83.05% decrease. To achieve this reduction, active measures to reduce the LCOE must be implemented. The strategy outlined below is not without difficulties, however it could be a suitable procedure to reach the commercial stage of UGEN and WEC in general ahead of the expected timeline. The release of property patents by the automobile company Tesla has promoted an ever increasing number of investors and researchers to enter into the development of the electric car. This increase of new research is expected to generate new ideas and concepts. Moreover, the lobbies of the traditional car manufacturers have seen their power reduced as the electric car market begins to develop a greater dimension in terms of investment and labour. The TRL of the electric car is expected to achieve level 9 (commercial stage) earlier due to the reasons outlined above.

The release of the patents involved in the WEC industry would theoretically create an increase of the interest and attraction of investors and researchers; presuming that this has the same results that the Tesla patent release generated.

Although releasing the patents would push the wave energy industry forward, it is a risky strategy that might not convince all the WEC patent owners. Another solution, along the same line as the strategy explained earlier would be to incite agreements between the competitors within the market. This kind of agreement between different companies or organisations with a common goal are called ‘joint ventures’ in technological innovation. A joint venture is an association of two or more individuals or companies engaged in a solitary business enterprise for the purpose of accomplish a specific task. The wave energy industry would benefit and develop if these kind of agreements were incited.

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Annex

Annex A. Diagram with the types of PTO for WECs. The definition of each type and some examples.

OSCILLATING WATER COLUMN (OWC)

Most devices are opened bellow the water surface has air trapped inside. This air is compressed and decompressed due to the motion of the waves that raise the level of the water inside. This high and low pressure of the air impulse a turbine, normally a Wells turbine. Exception is made to UGEN with an assymetrical floater with an internal OWC composed by a U-tank partially filled with water in 2 duct connected by a horitzontal duct where a reversible turbine is installed.

- **Fixed structure**
  - Isolated: Pico, LIMPET.
  - In breakwater: Sakata, Mutriku.
- **Floating**
  - Floating: Mighty Whale, Ocean Energy, Sparboy, Oceanlinx, UGEN.

OSCILLATING BODIES

The bodies can be floating or fully submerged. The system relays on two main parts and the relative movement between them.

Essential translation (Heave): One part is easily raised and descended with the motion of the waves whereas the other part is more unwilling to move. The relative movement between both parts actuates a lineal electrical generator, a pelton turbine or a hydraulic system.

Rotation: This devices take advantage of the difference of height in the different parts of a wave. Inducing a rotation or articulation that is used to pump high pressure oil, slide a mass, pump a hydraulic system...

- **Floating**
  - Essentially translation (heave): AquaBuoy, IPS buoy, FO3, Wavebob, PowerBuoy.
  - Essentially rotation: Pelamis, PS Frog, SEAREV.
- **Submerged**
  - Essentially translation (heave): AWS.
  - Rotation (bottom-hinged): WaveRoller, Oyster.

OVERTOPPING

The device captures the water that is close to the wave crest and introduce it, by over spilling, into a reservoir where it is stored at a level higher than the average free-surface level of the surrounding sea. The potential stored energy is converted through low-head hydraulic turbines.

- **Fixed structure**
  - Shoreline (with concentration): TAPCHAN.
  - In breakwater (without concentration): SSG.
- **Fixed structure (with concentration)**
  - Wave Dragon.

Annex B. OWC devices which have been developed since the 1940s until actuality.

Location Name	Date	OWC type	PTO type	Rated Power	Comments
Before 1990					
Japan **Masuda's buoy** [8, 52]	1940s	Floating buoy	Conventional unidirectional air turbine	Low	Navigation buoy. Was required a system of rectifying valves.
Japan **Kaimei** [8, 52]	1978	Large barge	Unidirectional and self-rectifying air turbines	-	13 chambers built in the hull. For testing.
Japan **Sanze** [5]	1983	Shore-fixed	Wells turbine	40 kW	Turbine previously tested in Kaimei.
Norway **Toftestallen** [5]	1985	Shore-fixed (cliff)	Vertica-axis Wells turbine	500 kW	Lower power than expected. Destroyed in 88.
Japan **Backward Bent Duct Buoy** [8]	1986	Floating device	-	-	First floating device. L shaped.
Japan **Port of Sakata** [5]	1990	Integrated into a break-water	Wells turbine	60 kW	First plant integrated into a breakwater.
India **Trivandrum** [5]	1990	Bottom-standing	Wells turbine and impulse turbine	125 kW	Used to test different types of turbines.
Scotland [5]	1991	Shoreline	Wells turbine	75 kW	Prototype.
Since the early 90s					
1.Fixed structures					
Portugal (Azores) **Pico Plant** [53]	1991	Fixed structure	Wells turbine	400 kW	Still operating. Stands on the sea bottom, adjacent vertical cliff.
Scotland [54]	2000	Fixed structure	Wells turbine	500 kW	Built in a recess carved into a cliff.
Scotland **OSPREY** [5]	1995	Nearshore bottom-standing	-	1 MW	Destroyed by the sea. Short life.
China **Guangdong** [5]	2001	Shoreline plant	-	100 kW	-

Australia **Oceanlinx** [5]	2014	Bottom-standing	-	1 MW	Had to be left aground.
South Chorea **Yongsoo** [5]	2014	Bottom-standing	-	500 kW	About 1 km off the coast.
2.Breakwater-integrated OWC					
Japan **Port of Sakata** [5]	1990	Into a breakwa-ter	Wells turbine	60 kW	First plant integrated into a breakwater.
Italy **Civitavecchia** [55]	2004	Into a breakwa-ter	-	-	17 caissons and 136 OWCs. Different geometry.
Spain **Mutriku** [56]	2008	Into a breakwa-ter	Wells turbine	296 kW	16 chambers rated in 18.5 each
3.Floating structure OWCs					
Japan **Mighty Whale** [57, 58]	1998	Floating platform	Wells turbine	110 kW	Three air chambers located at the front.
Ireland **1:4th scale BBDB** [59, 60]	2008	Floating buoy	Wells turbine and later axial-flow self-rectifying impulse turbine	-	1:4th scale of the BBDB designed in 1896 in Japan.
Australia **Oceanlinc Mk3** [5]	2010	Floating platform	Two different turbines	2.5MW	Floating platform with 8 chambers
United Kingdom **OWC spar-buoy** [60, 62]	2012	Spar-buoy	Long vertical tube open at both ends, attached to a floater	-	The length of the tube determines the resonance frequency of the inner water column. **¡Error! No se encuentra el origen de la referencia.**
4.Floating structure WECs with interior OWC					
Portugal **UGEN** [20, 63]	2010	OWC enclosed in a floating structure	Wells turbine or bi-radial turbine	-	An asymmetric floater with an interior U-tank partially filled with water and air. The motion of the water induces the motion of the air. The air impulse a turbine.

Buoyant tethered submerged [64]	-	Buoy submerged	Air turbine	-	A buoyant tethered submerged circular cylinder allowed to pitch freely about an axis below its centre. The pitching motion of the cylinder in waves induces a sloshing motion inside the tank placed in the cylinder.
Device with compressible air volumes and water columns [65]	-	Fixed on the bottom or floating	-	-	Consists in an air-filled box. The moving interface between enclosed air and the surrounding sea water generates the flow of air.

Annex C. PTOs that have been proposed and studied for the Salter's duck device.

PTOs studied for the Salter's duck	
Year and PTO	**Working principle**
1974, Stephen Salters first publication.	Two cylinders with ridges, between them there is another cylinder coupled to the vane. The space between surfaces is fulfilled with water. The movement of the vane transfers pressure to the water which passes through a turbine [6].
1983, new design developed by UK Wave Energy Programme.	A gyroscope is placed in what it's called the power canister, located inside the vane. The gyroscope is connected to a pump which pressurizes oil [26].
1998, redesign developed to improve the PTO performance.	Single ring cam system within a power toroid in the middle of each Duck. The ring cam is fixed to a plate, which is attached to the Duck beak and so it moves back and forth with respect to the ring cam pumps as the Duck "nods". This movement activates the pistons of the ring cam pumps, thereby supplying hydraulic oil to a high pressure manifold [26].
2007, a company call Weptos use the Salter's shape coming up with another PTO.	The spin is attached to a common axis that rotates. When a wave hits an individual rotor, the mechanics of the joint axle causes it to rotate. After a wave has passed the individual rotor, the centre of gravity makes the rotor swing back towards the starting point [66].

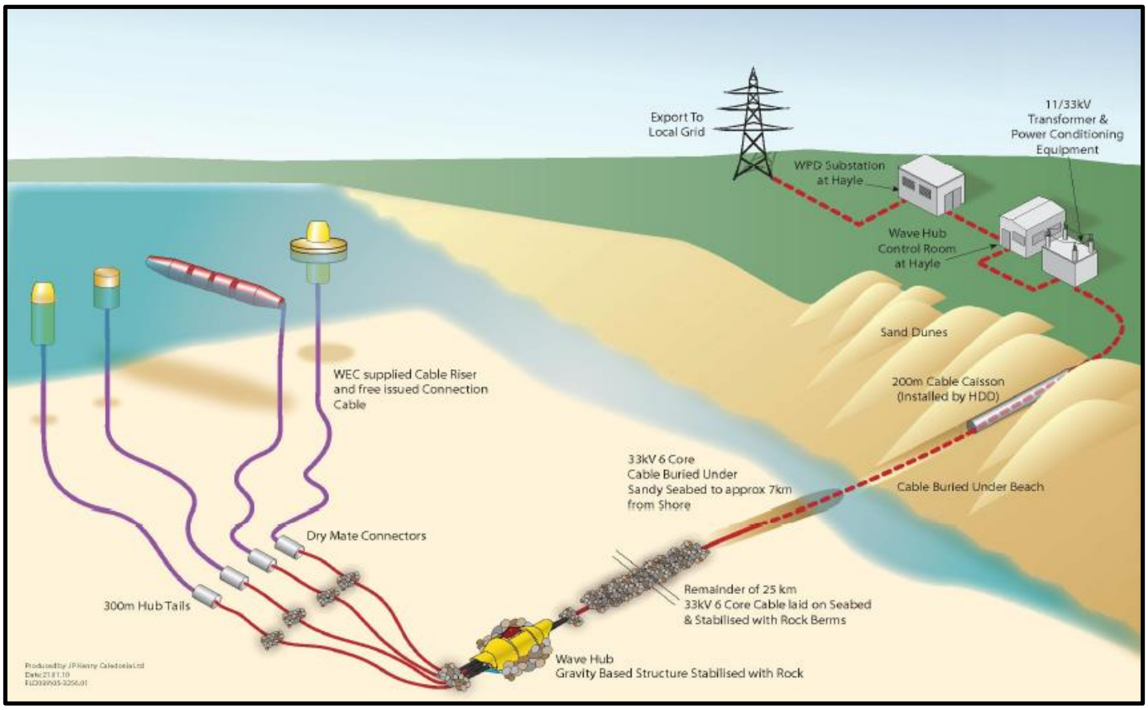
Annex D.1. Input variables of the section Energy in the WavEC techno-economic model.

	Concept / Explanation	Value
Electricity production	Losses	
	Mechanical losses [%]. The power matrix already includes the mechanical losses.	0
	Electrical PTO losses [%].	10

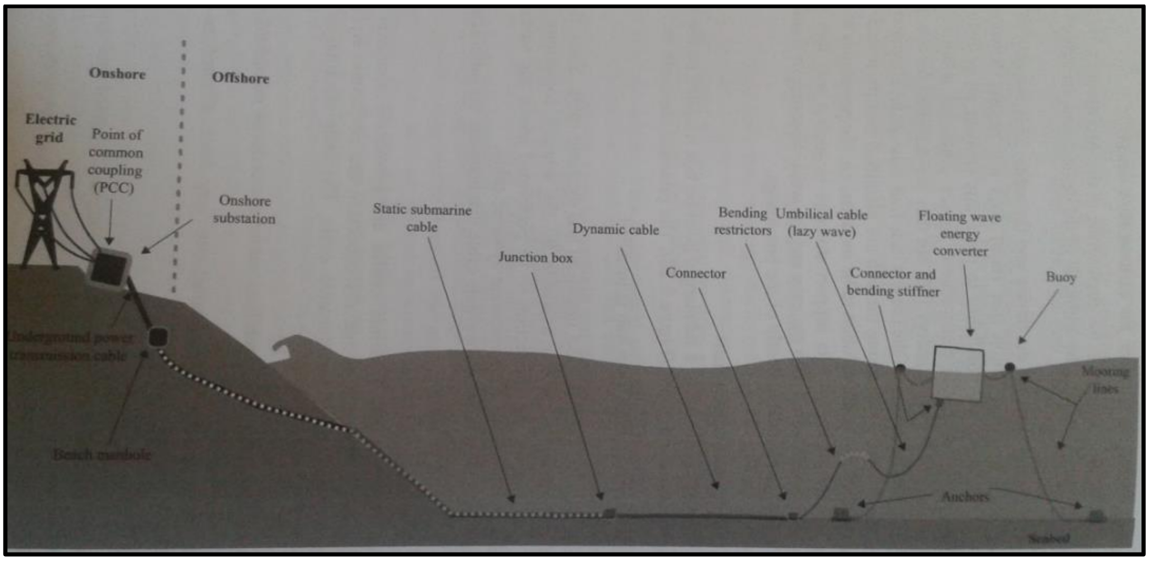
Annex D.2. Input variables of the section LCOE in the WavEC techno-economic model.

	Concept / Explanation	Value
Generic inputs	Discount rate [%]. [27]	10
	Construction period [years]	3
	Project lifetime [years]	20
	Decommissioning costs. [38]	5 % of the CAPEX

Annex E.1. Offshore electrical configuration of the Wave hub [31].



Annex E.2. Offshore electrical configuration proposed in reference [30]. The aim of the design is to minimize the length of the umbilical cable to reduce the stress of this cable.



Annex F.1. Project development costs.

PROJECT DEVELOPMENT			
Activity	Reference	Price [k€]	Farm cost [k€]
Project Management			104
Project Management	[31, 49]	3 % of CAPEX	104
Surveys			510
Marine Sea Bed surveys	[31, 50]	100	100
Environmental Survey	[31, 49, 50]	130	130
Wind & wave climate survey	[31]	70	70
Traffic & navigation survey	[31]	110	110
Real resource data assessment	[50]	50	50
Engineering consulting fees			176
EIA (Environmental impact assessment)	[31, 49, 50]	90	90
Grid connection studies	[31]	40	40
FEED (Front engineering end design)	[31, 49]	2% of CAPEX	46
Legal & financial costs			2,213
Lease from authorities	[31, 49, 50]	0.02 % of CAPEX	254
Insurance	[50]	1.5 % of CAPEX	1,908
Legal support	Assumed legal advisors for value of 50 k€	50	50
TOTAL PROJECT DEVELOPMENT			**3,003**

Annex F.2. WEC manufacturing costs.

WEC MANUFACTURING					
Component	Reference	Price	Units	Cost per device [k€/device]	Farm cost [k€]
Structure				1,210	48,380
Structure	[36]	2,950k€/tonne of steel	410 tonnes	1,210	48,380
PTO system				736	29,440
Turbine, valves and ducting system	[34] The cost is a function	-	-	472	18,880

	of the diameter of the turbine (2,75 m)				
Generator, power electronics, transformer, circuit breakers, switch boards and cabling	[34] The cost is a function of the power rate of the device (500 kW)	-	-	264	10,560
Ancillary system				53.65	2,146
Ballast system	[Estimated quotation based on WavEC expert]	23.64 k€	1 unit	24.10	964
Control system	[68]	30 k€	1 unit	30	1,200
Main structure assembly & installation				15.20	608
Technicians	[69]	3.04 k€/day	5 days	15.20	608
Station keeping system				179	7,180
Mooring lines	[70] 181.2 k€/m +20% for transport	28 k€/mooring line	3 mooring lines	83	3,327
Anchor	[36]	32 k€/mooring line	3 mooring lines	96	3,853
TOTAL WEC MANUFACTURING				**2,194**	**87,753**

Annex F.3. Electrical connection equipment costs.

ELECTRICAL CONNECTION EQUIPMENT					
Component	Reference	Price	Units	Cost per device [k€/device]	Farm cost [k€]
Umbilical	[71]	300 k€/km	6.12 km	45.90	1,836
Connectors		150 k€/unit	40 units	150	6,000
Dynamic Cable		100 k€/km	0.91 km	2.28	91
Junction boxes		150 k€/unit	5 units	18.75	750
Static Cable		100 k€/km	1.17 km	2.93	117

Main junction box		250 k€/unit	1 unit	6.25	250
Export cable		150 k€/km	5.85 km	21.95	878
TOTAL ELECTRICAL CONNECTION EQUIPMENT				**248.05**	**9,922**

Annex F.4. Assembly, installation & commissioning.

ASSEMBLY, INSTALLATION & COMMISSIONING					
Component	Reference	Price [k€/day]	Units [day/unit]	Cost per device [k€/device]	Farm cost [k€]
Installation of mooring system				60.67	2,427
Mob. & Demob. Crane	[72]	-	-	-	5
Mob. & Demob. Anchor handling vessel	[67]	-	-	-	100
Mob. & Demob. Support vessel	[73]	-	-	-	5
Mob. & Demob. ROV	[74]	-	-	-	10
Offshore work - Anchor handling vessel	[75]	25	0.97	24.19	968
Dock work - Anchor handling vessel	[75]	25	0.17	4.17	167
Crane	[72]	0,92	1.13	1.04	42
Support vessel	[73]	4	1.13	4.54	181
ROV	[74]	3	1.13	2.84	11
Technicians – Preparation in the dock	[69]	6.52	1.13	7.40	296
Weather downtime	[35]	-	-	-	781
Installation of electrical connection				349.55	13,982
Mob. & Demob. Cable layer vessel	[75]	-	-	-	350
Mob. & Demob. Multicat	[75]	-	-	-	18
Mob. & Demob. ROV	[29]	-	-	-	10
Mob. & Demob. Crane vessel	[75]	-	-	-	519
Mob. & Demob. Cable burial	[76]	-	-	-	4
Mob. & Demob. External protection	[76]	-	-	-	10
DC – Cable layer vessel	[75]	87.5	-	138.55	5,542
DC – Multicat	[75]	4.5	-	7.13	285
DC – ROV	[75]	2.5	-	3.95	158
SC – Cable layer vessel	[75]	87.5	1	24.95	998

SC – Multicat	[75]	4.5	1	1.28	51
SC - ROV	[74]	2.5	1	0.73	29
SC – Divers	[76]	4	1	1.15	46
SC – Cable burial	[76]	7	1	2	80
SC – External protection	[76]	13	1	3.70	148
CP – Crane vessel	[75]	129.75	1	36.96	1,479
CP – Multicat	[75]	4.5	1	1.28	51
CP – ROV	[75]	2.5	1	0.73	29
Weather downtime	[35]	-	-	-	4,176
Installation of main structure				37.68	1,507
Mob. & Demob. Quayside crane	[36]	-	-	-	330
Mob. & Demob. Tug vessel	[73]	-	-	-	20
Mob. & Demob. Support vessel	[73]	-	-	-	5
Mob. & Demob. ROV	[74]	-	-	-	10
Offshore work - Tug vessel	[73]	8	0.35	2.83	113
Dock work – Tug vessel	[73]	8	0.33	2.67	107
Quayside crane	[37]	9.8	0.69	6.75	270
Technicians – Preparation for towing in the dock	[69]	6.52	0.69	4.48	179
Support vessel	[73]	4	0.69	2.75	110
ROV	[74]	2,5	0.69	1.73	69
Weather downtime	[35]	-	-	-	572
Commissioning & testing				1.43	57
Mob. & Demob. ROV	[74]	-	-	-	12
Mob. & Demob. Support vessel	[73]	-	-	-	5
ROV	[74]	3	2	-	6
Support vessel	[73]	4	2	-	8
Divers	[76]	4	2	-	8
Weather downtime	[35]	-	-	-	18
TOTAL ASSEMBLY, INSTALLATION & COMMISSIONING				**449.33**	**17,973**

Annex F.5. Monitoring & miscellaneous equipment.

MONITORING & MISCELLANEOUS EQUIPMENT				
Component	References	Price	Cost per device [k€/device]	Farm cost [k€] (40 devices)
Monitoring			1	40
Monitoring	[31]	1	1	40
Support services infrastructure			5.65	226
Semi-rigid support vessel	[77]	35	0.88	35
Building, offices and parking	[31]	110	2.5	100
Power conditioning, control system and SCADA	[31]	41	1.03	41
Installation of control, monitoring and communication equipment	[31]	50	1.25	50
TOTAL MONITORING & MISCELLANEOUS EQUIPMENT			**6.65**	**266**